Weed Research

WILEY

ORIGINAL ARTICLE OPEN ACCESS

Performance of Sprayable Liquid Mulches Based on Industrial By-Products for Weed Control in Tree Nurseries

Marleena Hagner[1] | Riikka Keskinen[1] | Aleksi Kauhanen[2] | Jyrki Airaksinen[2] | Kyösti Ruuttunen[3] | Kimmo Rasa[1]

[1]Natural Resources Institute Finland (Luke), Jokioinen, Finland | [2]Natural Resources Institute Finland (Luke), Läyliäinen, Finland | [3]Natural Resources Institute Finland (Luke), Helsinki, Finland

Correspondence: Marleena Hagner (marleena.hagner@luke.fi)

Received: 26 October 2025 | **Revised:** 30 June 2026 | **Accepted:** 21 July 2026

Subject Editor: Diego Batlla

Keywords: fibre sludge | herbicide | mulching | pyrolysis liquid | wood vinegar

ABSTRACT

Sustainable new solutions for controlling weeds in tree nursery production are needed. This study assessed the performance of pyrolysis liquid containing sprayable fibre sludge mulch (FLM) compared with the corresponding peat-based mulch (PLM) and non-mulched control in forest tree nursery production. Experiments were conducted with grafts of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and European silver birch (*Betula pendula*). During the first growth period, the effects of mulches on the number and species of weeds and on soil temperature and moisture were assessed. Both mulches prevented weed growth equally during the first 6 weeks. Twelve weeks after mulching, the number of weeds in PLM was 1.9 and in FLM 3.3 times lower than in the non-mulched plots. Neither mulch affected the survival of the tree seedlings over the two monitored growing seasons. However, PLM increased spruce and birch growth significantly, while FLM reduced birch growth. The temperature and moisture of growing media were slightly lower in FLM treatment than in PLM or the non-mulched soil. The results indicate that liquid mulches provide a new alternative for weed control in tree nurseries. Analysing the techno-economic performance of FLM showed that it might well be economically feasible compared with manual weeding or currently available biodegradable mulches. The study highlights the potential of liquid mulches as an alternative to conventional practices, including black plastic and herbicide use, in the horticulture and agriculture sectors and supports the development of a circular bioeconomy by introducing new applications for industrial side streams and creating a more diverse toolkit for future weed management.

1 | Introduction

The prevailing weed management system based on chemical control is being seriously challenged due to the increase in weed herbicide resistance and the need to limit environmental and health hazards related to the use of synthetic chemicals (Bajwa et al. 2015; Heap 2026; Peterson et al. 2018). Sustainable and innovative new technologies and solutions for controlling weeds are thus urgently needed to complement and substitute existing practices (Harker and O'Donovan 2013; Westwood et al. 2018). In tree nursery production, targeted measures to combat weeds are particularly required, as the negative competitive effect of weeds is emphasised in the restricted growth media. Furthermore, the number of permitted herbicides is small and limited in efficiency, meaning laborious and expensive hand weeding is often still imperative (Case et al. 2005; Fennimore and Doohan 2008; Stewart et al. 2017). The global nursery stock market was worth USD 87.62 billion in 2019, with an expected annual growth rate (CAGR) of 5.7% between 2025 and 2033. This growth is fuelled by the rising popularity of ornamental plants for urban green spaces, residential landscaping and home gardens, along with increasing public awareness of environmental conservation and the importance of sustainable landscaping solutions (Data Insights Market 2025).

Covering soil with mulch is an age-old technique for preventing weed growth and gaining other benefits such as moisture conservation, temperature regulation, soil structure protection and improved nutrient use efficiency (Kasirajan and Ngouajio 2012). Plastic film mulch is used extensively, with positive effects on yield and water use efficiency, but its petroleum-based origin and difficulties related to removal and disposal have prompted the development of biodegradable alternatives (e.g., Gao et al. 2019; Goldberger et al. 2013). Although there are issues concerning durability, biodegradability and price, encouraging results in the functionality of bio-based biodegradable films and paper mulches have been reported (Briassoulis and Giannoulis 2018; Haapala et al. 2014; Liu et al. 2021). Paper-based biodegradable mulches have shown promising potential for weed control. In addition to being biodegradable, they may be particularly effective against certain weed species. For example, paper mulch has been shown to provide improved control of difficult perennial weeds such as *Cyperus rotundus* compared with polyethylene mulch (Cirujeda et al. 2012). These findings highlight the importance of mulch material properties in determining weed suppression efficacy. In recent papers, Hagner, Hyvönen, et al. (2020) and Hagner, Lindqvist, et al. (2020) introduced a novel pyrolysis liquid (PL) containing peat mulch (PLM), which is laid on the soil surface as a liquid suspension that forms a solid cover on drying. PL is produced as a by-product of biomass pyrolysis processes in the bioenergy and biochar industry, typically derived from lignocellulosic materials such as wood (Fagernäs et al. 2012). The ability of PLM to effectively inhibit weeds was attributed to the organic compounds contained in the pyrolysis liquid (e.g., acetic acid and other weak organic acids, furfural and phenols) in combination with the strong mechanical resistance of the crust comprised of peat fibres glued together by the sticky liquid. PLM was patented in Finland in 2019 (patent number FI127775B).

In addition to solid biodegradable mulches, sprayable or liquid mulches—often referred to as hydromulches—have been investigated as an alternative approach for weed control. These materials typically consist of lignocellulosic fibres, binders and water, forming a protective layer on the soil surface after application. Previous studies have demonstrated that hydromulches can reduce weed emergence under field and laboratory conditions (Warnick et al. 2006; Cirujeda et al. 2024; Durado et al. 2024). Although most hydromulch studies have focused on paper-based fibre systems, the present study differs in utilising industrial side-stream fibres and PL as functional components. Nevertheless, these approaches share similar mechanisms of weed suppression, including physical barrier formation and light exclusion.

The sustainability of a PLM innovation based on peat is questionable due to the very slow renewal rate of peat, and it contrasts with the long ongoing efforts of finding alternatives to peat exploitation in agri- and horticulture (Alexander et al. 2008; Kern et al. 2017). Replacing the peat in the PLM with a genuinely renewable fibrous material would therefore be desirable and would probably promote a market uptake of the product due to better acceptability. A new liquid mulch solution based on side stream fibres from the pulp and paper industry was therefore recently patented in Finland (FI2023/050709). Here, the peat was replaced with wood-derived cellulose fibres too short for the actual products (fibre sludge derived from the paper drying process, see e.g., Rasa et al. 2021). Currently, these organic side streams of the pulp and paper industry are mostly combusted for energy in the factory, with a relatively low coefficient of performance, and to some extent landfilled, applied as a soil improver, or integrated in various building materials (Faubert et al. 2016; Monte et al. 2009). Higher-value applications are nevertheless desirable.

This study aimed to assess the performance of pyrolysis liquid containing fibre sludge mulch (FLM) compared with the corresponding peat-based mulch (PLM) and non-mulched plots in forest tree nursery production. Experiments were conducted in transplant beds with grafts of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and European silver birch (*Betula pendula*). The effects of mulching on the weed number and species composition, the temperature and moisture beneath the surface of the growing media and the growth and survival of the tree seedlings were recorded. In addition, the impacts of raw mulching materials on direct contact with 4-year-old tree seedlings were assessed. The study's hypothesis was that an FLM solution supporting circular bioeconomy principles would prevent weed growth at least as well as a non-renewable peat-based PLM solution. We also predicted that mulching materials had no effect on the growth or survival of tree seedlings. Finally, the techno-economic performance of the proposed FLM solution was analysed, facilitating a comparison with existing weed control practices. The study aimed to assess the potential of these mulches to contribute to reducing the use of black plastic and herbicides in tree nursery production.

2 | Materials and Methods

The performance of novel biodegradable mulches, FLM and PLM, was studied in a 3-year field experiment conducted under practical tree nursery conditions at Natural Resources Institute Finland's Haapastensyrjä Research station in Loppi, southwestern Finland (60.618814, 24.436005). During the first growth period (2021), the mulches' weed suppression ability and their effects on soil condition were investigated. The height of tree seedlings was measured after the growing season in 2021 and 2022, whereas in the third year (2023), the focus was on assessing the possible harmful impacts of direct FLM and PLM contact with the seedlings.

2.1 | Production of the Mulching Materials

The mulching materials were produced by mixing tap water, peat or fibre sludge and pyrolysis liquid (PL) (Table 1). The peat used was homogeneous, unfertilised white Sphagnum peat with a pH of 3.9 and an EC of 37 mS/m. For the mulch, the peat was sieved with a 4 mm sieve. The fibre sludge originated from a paper mill sludge factory (Stora Enso's Imatra Mill) in southeastern Finland. It consisted of nutrient-poor cellulose material from the pre-clarifier of cardboard machine process water, removed in a wire sieve as semi-dry mass, being too short for the mill's final product. The fibre had a pH of 8.6 and an EC of

TABLE 1 | Proportions of substances in various mulching materials.

Treatment	Application year	Application rate $L\,m^{-2}$				
		Peat	Fibre	Water	PL	Mulch
Peat + PL 4% (PLM4)	2021	18.0	—	10.0	0.8	20.0
Fibre sludge + PL 4% (FLM4)	2021	—	6.0	14.0	0.8	20.0
Fibre sludge + PL 2.5% (FLM2.5)	2023	—	5.4	12.15	0.45	18.0
Fibre sludge + PL 5% (FLM5)	2023	—	5.4	11.7	0.9	18.0

15 mS/m and was used as perceived. Further details of the fibre sludge are given in Rasa et al. (2021; Supplementary materials S2, table S1). The PL used was produced from birch (*Betula* sp.) wood in a commercial producers' continuous retort C (450°C, holding time 2 h) as described by Fagernäs et al. (2012). During the slow pyrolysis, a composite sample of the total distillate was collected. After settling for 2 weeks, the aqueous and tar fractions were separated by a 30% water addition and decanting. Only the aqueous fraction was used in the experiments. The pH of used PL was 2.8. The same PL has also been previously used in our other experiments (Hagner, Hyvönen, et al. 2020; Hagner, Lindqvist, et al. 2020; Hagner et al. 2021), and its detailed characteristics are given in Hagner, Hyvönen, et al. (2020; table 1).

The mulch constituents were mixed in 100 L buckets using a twist drill (5 min, 300 rpm). The final PLM had an EC of 77.7 mS/m and a pH of 3.55, and the corresponding values for FLM were 75.6 mS/m and 5.08 respectively. Mulches were spread as a liquid using tailor-made equipment consisting of a 100 L bucket, a destructive submersible pump and a drainpipe (diameter 30 mm) (Figure S1). The application rate of $20\,L/m^2$ corresponds to 200 000 L/ha. Based on the composition of the mulching materials, the corresponding amounts of fibre sludge, PL (when using FLM4) and water per hectare are approximately 60 000, 8000 and 140 000 L/ha respectively.

2.2 | Experimental Conditions

The mulching treatments were carried out on a growth bed composed of a 30 cm layer of peat smoothly compacted by irrigation. The growing media consisted of fertilised (Yara Hevi2: N 9.9%, P 1.9%, K 24.5%, S 12.0%, B 0.03%, Mn 0.4%, Zn 0.16%; $1\,kg/m^3$) and limed (Nordkalk: Ca 36%; $4\,kg/m^3$) commercial *Sphagnum* peat. The test plants were 2-year-old spruce (*P. abies*: height 22–25 cm) and birch (*B. pendula*; height 32–35 cm) seedlings, which were bought from Fin Forelia Oy and 1-year-old pine seedlings (*P. sylvestris*: height 22–26 cm), which were produced locally in Natural Resources Institute Finland's nursery in Haapastensyrjä. Seedling heights were measured at the time of planting.

The experiment started at the end of May 2021 and continued until October of 2023. In 2021, the mean summer (May–July) temperature was 18.1°C and precipitation was 191 mm. In 2022, the corresponding values were 17.4°C and 155 mm. Both years were therefore warmer (+1.6°C–2.3°C) and drier (c. 10%–27%) than the region's long-term average (20 years) (Finnish Meteorological Institute 2021). The mean growing period temperate sum (GDD) calculated as the cumulative daily mean temperature above a base temperature of 5°C during the growing season in both years was between 1100 and 1350. Meanwhile, the temperature in 2023 corresponded to the average level (16.4°C), whereas precipitation was 10% higher (231 mm) than the area's 20-year average.

2.3 | Experimental Setup

The experimental layout involved four 3.5 × 4.5 m blocks (A–D), illustrated in Figure 1. The mulching treatments were randomly arranged within the blocks by dividing each block into three main plots of 3.5 × 1.3 m, with access strips of 0.2 m between them. The main plots were later further divided into three subplots (1.17 × 1.3 m) to include the three different tree species. The experiment thus contained a total of 36 experimental plots (four replicate blocks, three mulching treatments and three tree species; Figure S2).

The main plots were randomly covered with (1) PLM4, (2) FLM4, or (3) left non-mulched, each in four replicates. The applied mulch layer ($20\,L/m^2$) corresponded to an approximate thickness of 2 cm in its wet form (for each treatment). After application, the mulch dried to form a continuous and relatively solid surface layer on the growing medium, resulting in a thinner compacted layer. After a stabilisation period of 2 weeks (Hagner, Hyvönen, et al. 2020), the birch (*B. pendula*), spruce (*P. abies*) and pine (*P. sylvetris*) seedlings were planted (on 7 June 2021) in the subplots in six parallel rows, each containing five seedlings. The total number of seedlings was therefore 30 per subplot (Figure 1). Prior to planting, the mulch cover was punched with a specific wooden tool to form planting holes of 6 × 6 cm wide for each of the seedlings.

As 2021 and 2022 were drier than average in Finland, top irrigation was applied once a week or every 2 weeks, depending on natural rains according to the normal seedling production protocol. After drying, the mulch formed a relatively solid surface layer. Top irrigation did not disrupt the mulch layer, although temporary softening and minor structural changes at the surface were observed.

In 2021, the number of weeds in the plots was assessed 6 and 12 weeks after mulching. All weeds were counted and identified to species level, after which they were uprooted. Due to the short growing season in northern conditions, weed emergence is concentrated in the early part of the growing period. In PLM and FLM treatments, no weeds were observed in week

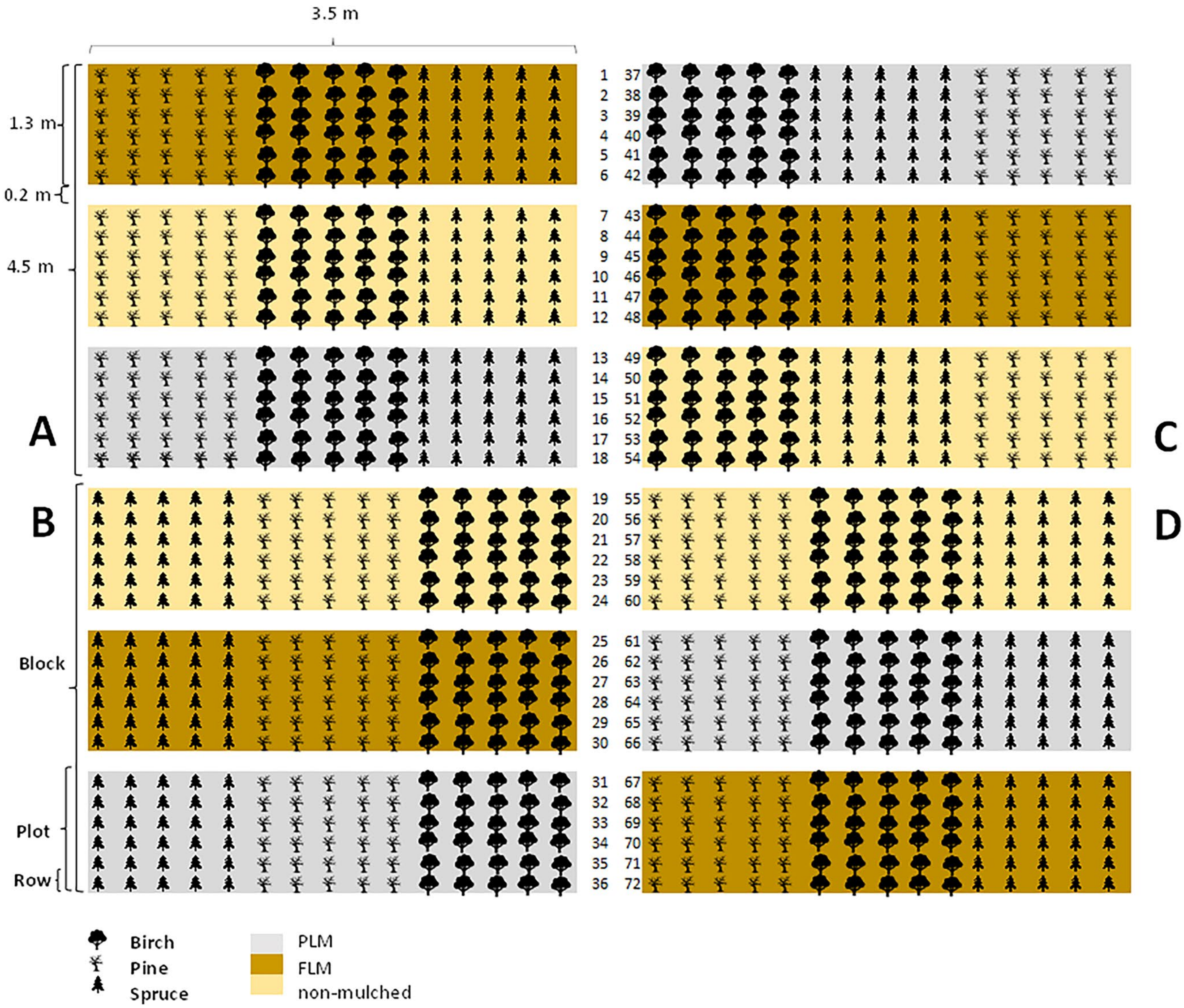

FIGURE 1 | The setup of the experiment consisted of four blocks (A–D), each divided into three main plots, which were further divided into three subplots encompassing three plant species planted in six parallel rows. Four of the main plots were treated with either peat (PLM) or fibre sludge (FLM)-based mulching material, and four were left without a mulch.

6 and weeds were therefore uprooted only in week 12 (results expressed per m^2). The survival of birch, pine and spruce seedlings and their height (cm) were assessed after the first growing period in October 2021 and after the second growing period in October 2022. To avoid marginal effects, the observations of weeds and seedlings were conducted from the central area (80 × 80 cm) of each subplot, including 12 seedlings of each species. Weed emergence in 2022 and 2023 was not systematically assessed, as the focus of the study shifted to seedling growth and the effects of mulching on soil conditions and plant performance.

The effects of treatments on the temperature and moisture of the growing media were measured during the 2021 growing period at 10 min intervals using TMS Standard dataloggers (Wild et al. 2019). The sensors were placed in the middle of the pine growing subplots ($n = 4$) at a depth of 6 cm. The pH and electrical conductivity of peat and fibre as raw materials and as ready mixed mulch material were measured (1:5 H_20). Soil pH and electrical conductivity in the non-mulched soil and beneath the mulches were measured at 4 weeks after mulching from 10 cm topsoil including mulch.

2.4 | Re-Mulching in 2023

To assess the impact of direct contact between the mulching materials and 3-year-old pine seedlings and 4-year-old spruce and birch seedlings, the experimental field was reorganised. On 6 June 2023, every other seedling was removed so that only 15 seedlings of each species were left per subplot (Figure 1). Thereafter, all weeds were manually removed, and the subplots were subsequently divided lengthways into three sections (2 rows of seedlings in each). These sections were treated with FLM2.5 and FLM5 (18 L/m^2) (Table 1) or left without mulching (non-mulched plots), making up 12 replicates for each treatment with each tree species. These two formulations were selected to represent a lower and higher concentration range of PL, enabling evaluation of the potential dose-dependent effects of the mulching material on seedling survival under direct contact. The mulches were spread so that the tree base was in contact with the mulching material (Figure S3). Four months after mulching, the survival of trees was assessed to determine if the direct contact with the mulching material was detrimental for the pine, birch and spruce seedlings.

2.5 | Statistical Analyses

The experimental setup was based on a strip-plot design in four randomised blocks. The selection of explanatory variables and interaction terms depended on the specific dataset and experimental design for each variable. Depending on the analysed variable, the total number of observations (individual measurement points per variable) varied greatly (12–2928), as the measurements were targeted differently across variables. This procedure affected the linear mixed model applied for the variables. For the number of weed species, the mulching treatment (PLM, FLM, or non-mulched), tree species (birch, pine, or spruce) and their interaction were the explanatory (fixed) factors in the model. The interaction term was tested but was not statistically significant, and therefore the comparisons are presented within each species. The weed species with only a few observations per plot were not analysed. For the temperature and moisture of the growing media, the mulching material, month, time of day [night (8 p.m.–8 a.m.) or day (8 a.m.–8 p.m.)] and day of the month (only for temperature) with specific interactions were used as the explanatory factors. Appropriate random factors with covariance structures were included in the model to account for the correlation and variance of observations for the analysed variable, which was assumed to be normally distributed (usually after transformation). For growth of tree species, analyses were conducted separately for each species, with mulching material as the only fixed explanatory factor, and block was a random factor. The Bonferroni method (with an overall significance level of 0.05) was used in pairwise comparisons of model-predicted class means. The statistical analyses were performed with the SAS 9.4 software's GLIMMIX procedure.

2.6 | Estimating the Techno-Economic Performance of the Liquid Mulch

The estimation of the techno-economic performance of the liquid mulch started with constructing the material and energy balances for manufacturing the mulch. The production of the mulch is supposed to take place in the vicinity of the seedling plots. The mulch can thus be manufactured as required, and the transporting distance for the mulch is minimised.

The manufacturing process is described in Figure 2. The liquid mulch is assumed to be manufactured using a batch process, in which a defined quantity of raw materials is mixed and prepared at one time to produce a single batch sufficient for covering a specific area (e.g., 100 m^2). The composition of the FLM used in techno-economic calculations corresponds to the FLM4 (Table 1), but the material amounts are presented in mass units rather than volume units. For conversion, it was assumed that the density (d) of the original fibre sludge was 0.175 o.d. kg/L, and the dry matter content (DMC) was 33.5% (Rasa et al. 2021; in their Supplementary materials S2, table S1). The assumed PL density was 1.13 kg/L (Hagner, Hyvönen, et al. 2020).

The FLM is applied on the field as a suspension with tailor-made equipment consisting of a large container transported with a tractor, a destructive submersible pump and a drainpipe (diameter 30 mm) (Figure S1). The mulching speed is approximately 100 m^2/h, based on the authors' practical observations under field conditions, including handling and transport time.

The total cost of the FLM utilisation includes the cost of materials, manufacture and application of the product. The raw materials and their estimated prices, as well as the costs of the required manual labour, energy and equipment, are presented in Table 2.

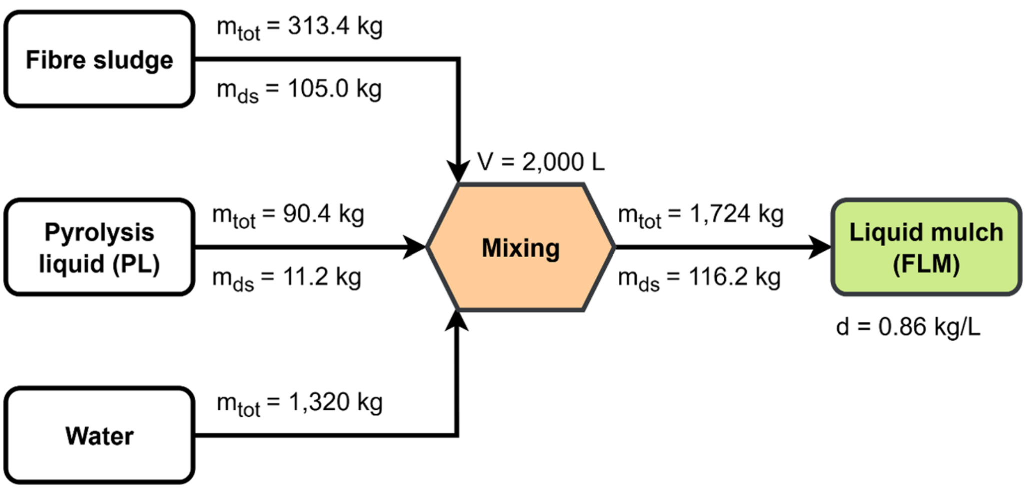

FIGURE 2 | Process for preparing a batch of FLM for mulching a 100 m^2 field area. PL is pumped, and water is added from the tap with a hose into the mixing vessel (volume 2000 L), while fibre is added with a tractor's front loader, for example. A destructive submersible pump stirs the suspension, circulating it in the vessel for 1 h. The produced FLM is readily transportable to the nearby field to be mulched. Symbols: m_{tot} = total weight of the stream (including moisture); m_{ds} = dry solids weight of the stream (excluding water); d = density.

TABLE 2 | Raw materials, their estimated prices and costs of required energy, equipment and manual labour used in techno-economic calculation for FLM manufacture and application.

Item	Cost (€/unit)	Unit	Notes
Cellulosic fibre (fibre sludge)	0.00	o.d. kg	Side stream, no commercial value
Pyrolysis liquid (PS)	300.00	m^3	Side stream, limited comm. val.[a]
Tap water, cold	2.52	m^3	Information available online[b]
Electricity	0.11	kWh	Information available online[c]
Transport	62.44	h	Including all costs[d]
Tractor use	5.00	h	Including fuel and other vehicle costs
Employee (agriculture sector)	25.46	h	Including salary and indirect costs[e,f]
Rental pump (submersible)	25.00	d	Rented from a commercial operator

[a]Uotila et al. (2025).
[b]Water News Europe (2021). https://www.waternewseurope.com/water-prices-compared-in-36-eu-cities/.
[c]StatFin (2025).
[d]Includes fuel, vehicle and personnel costs for truck transport, as specified in Uotila et al. (2025).
[e]StatFin (2024).
[f]Suomi.fi (2025).

In Table 2, the information about agricultural sector wages was obtained from a public database (Statistics Finland, Tilastokeskus). As the level of the indirect costs, 45% of the salary was used and included in the employee costs: the agricultural sector employee costs include €17.56/h + €7.90/h salary and indirect costs. For certain prices (fibre sludge, tractor use, pump rental cost), no published figures were found. These items are therefore estimates based on the authors' experience.

3 | Results

3.1 | Effects of Mulches on Weed Occurrence

After 6 weeks, no weeds were grown in the PLM- and FLM-treated plots. Instead, in the non-mulched plots, the mean number of weeds was 26 individuals/m^2 (Figure 3). After 12 weeks, fewer weeds occurred in both mulch treatments than in the non-mulched plots, but the difference was statistically significant only for FLM plots (−70%) ($p = 0.032$). In the PLM plots, the reduction

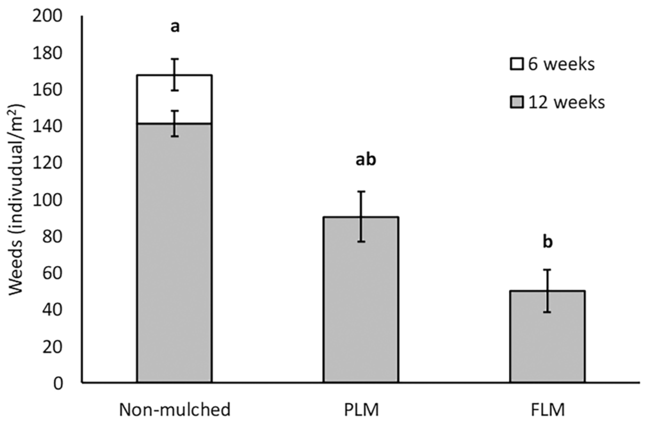

FIGURE 3 | Total number of weeds in non-mulched plots and in plots treated with mulches based on peat (PLM) or fibre (FLM) amended with pyrolysis liquid (mean ± SE) at 6 and 12 weeks after treatments. Statistical differences ($p < 0.05$) between treatments: Total weed number after 12 weeks is denoted with different letters above the error bars.

in weed numbers from the non-mulched plots was 46%, but due to high variation the difference was not statistically significant.

In general, there were fewer individual weed species in PLM and FLM than in the non-mulched plots (Table 3). However, the variation among replicates was high. The weed community was dominated by annual and wind-dispersed species such as *Senecio vulgaris* and *Taraxacum officinale*, indicating colonisation from surrounding areas during the early growing season. However, only the numbers of broad-leaved weeds *Chamaenerion angustifolium* and *Ranunculus repens* individuals differed significantly between the FLM and non-mulched plots, being four and seven times lower in the FLM treated plots respectively ($p < 0.05$). Furthermore, the number of *Taraxacum officinale* individuals was four times lower in PLM and FLM than in the non-mulched plots, but the difference was not statistically significant ($p > 0.05$).

3.2 | Effects of Mulches on the Growth and Survival of Tree Seedlings

Birch seedlings grew significantly faster than pine and spruce ($p < 0.0001$). Neither FLM nor PLM treatments affected the pine seedling height in 2021 or 2022 (Table 4).

Instead, spruce seedlings grown with PLM were significantly higher (c. 3–4 cm) than those grown in the non-mulched or FLM treatments in 2021. A similar trend was also observed in 2022, even though the difference was statistically significant only for FLM. Over the 2-year period, PLM resulted in significantly higher spruce seedling height (approximately +7 cm) compared with both non-mulched or FLM treatments (Table 4).

In 2021, birch seedlings grown in the PLM treatment were significantly higher (> 16 cm) than in the non-mulched or FLM treatments. In 2022, birch seedling height was significantly lower in FLM treatment than in the PLM and non-mulched treatments. After the two growing periods, birch grown in

TABLE 3 | Number of individual weeds per species per m^2 at 12 weeks after mulching in treatments with PLM (peat + pyrolysis liquid) and FLM (0-fibre + pyrolysis liquid) and in non-mulched plots.

	Non-mulched	PLM	FLM
Alnus sp.	0.39 ± 0.23 a	0.17 ± 0.17 a	0.00 ± 0.00 a
Cerastium fontanum	0.00 ± 0.00 a	0.33 ± 0.33 a	0.00 ± 0.00 a
Chamaenerion angustifolium	22.2 ± 4.39 a	19.4 ± 4.41 a	**5.53 ± 1.83 b**
Cirsium arvense	1.23 ± 0.11 a	0.67 ± 0.47 a	0.67 ± 0.48 a
Equisetum arvense	7.03 ± 2.96 a	3.67 ± 1.82 a	5.00 ± 3.68 a
Gnaphalium uliginosum	1.11 ± 0.66 a	0.50 ± 0.17 a	0.83 ± 0.83 a
Juncus bufonius	0.50 ± 0.32 a	0.00 ± 0.00 a	0.00 ± 0.00 a
Persicaria lapathifolia	0.32 ± 0.21 a	0.33 ± 0.19 a	0.17 ± 0.17 a
Plantago major	0.17 ± 0.14 a	0.27 ± 0.17 a	0.00 ± 0.00 a
Poaceae sp.	0.78 ± 0.49 a	1.17 ± 0.79 a	0.33 ± 0.19 a
Ranunculus repens	49.6 ± 13.2 a	25.3 ± 10.8 a	**5.20 ± 1.69 b**
Rubus idaeus	0.11 ± 0.06 a	0.33 ± 0.19 a	0.17 ± 0.17 a
Rumex acetosa	0.50 ± 0.32 a	0.33 ± 0.33 a	0.33 ± 0.33 a
Rumex sp.	0.67 ± 0.47 a	0.33 ± 0.19 a	0.33 ± 0.33 a
Salix sp.	3.86 ± 1.56 a	0.50 ± 0.32 a	1.00 ± 0.43 a
Senecio vulgaris	34.6 ± 11.8 a	23.7 ± 13.8 a	21.8 ± 12.4 a
Stellaria media	0.00 ± 0.00 a	0.67 ± 0.67 a	0.00 ± 0.00 a
Taraxacum officinale	41.6 ± 9.68 a	11.8 ± 2.79 a	9.92 ± 2.31 a
Trifolium repens	0.11 ± 0.11 a	0.00 ± 0.00 a	0.17 ± 0.17 a
Tripleurospermum inodorum	0.00 ± 0.00 a	0.00 ± 0.00 a	0.17 ± 0.17 a
Vicia sp.	1.33 ± 1.00 a	0.33 ± 0.19 a	0.17 ± 0.17 a
Total weed number	167 ± 6.95 a	90.5 ± 13.7 ab	50.0 ± 11.5 b

Note: $N = 4$, the values are means ± SE ($n = 4$). Statistical differences marked with letters, treatments with different letters are significantly different ($p < 0.05$).

TABLE 4 | Mean (±SE) heights (cm) with key statistical parameters and treatment effects for birch, pine and spruce seedlings grown with pyrolysis liquid containing peat mulch (PLM), fibre mulch (FLM), or non-mulched plots in 2021, 2022 and over the two consecutive years.

							Estimated height (cm)		
Species	Year	No. of observations	No. df	Den df	*F* value	*p*	Non-mulched	PLM	FLM
Birch	2021	144	2	138	34.6	< 0.0001	43.8 ± 7.31 a	62.5 ± 7.60 b	46.1 ± 4.95 a
	2022	144	2	138	11.6	< 0.0001	84.3 ± 2.43 a	77.8 ± 4.62 a	68.1 ± 7.36 b
	2021–2022	144	2	138	16.4	< 0.0001	128 ± 6.46 a	140 ± 11.1 c	114 ± 8.47 b
Pine	2021	144	2	138	0.49	0.616	11.1 ± 0.61 a	11.5 ± 0.46 a	10.7 ± 0.26 a
	2022	142	2	136	1.92	0.150	29.1 ± 0.79 a	28.8 ± 1.62 a	28.3 ± 1.73 a
	2021–2022	142	2	136	2.15	0.121	40.2 ± 0.87 a	40.3 ± 1.88 a	39.0 ± 1.84 a
Spruce	2021	141	2	135	14.2	< 0.0001	11.5 ± 1.01 a	15.9 ± 1.47 b	12.1 ± 0.61 a
	2022	141	2	135	3.39	0.037	25.8 ± 1.42 ab	28.5 ± 1.20 a	25.0 ± 3.31 b
	2021–2022	141	2	135	10.2	< 0.0001	37.4 ± 1.17 a	44.4 ± 0.54 b	37.1 ± 3.61 a

Note: Within each row, treatments with different letters are significantly different ($p < 0.05$). Comparisons are made separately within each species and year.

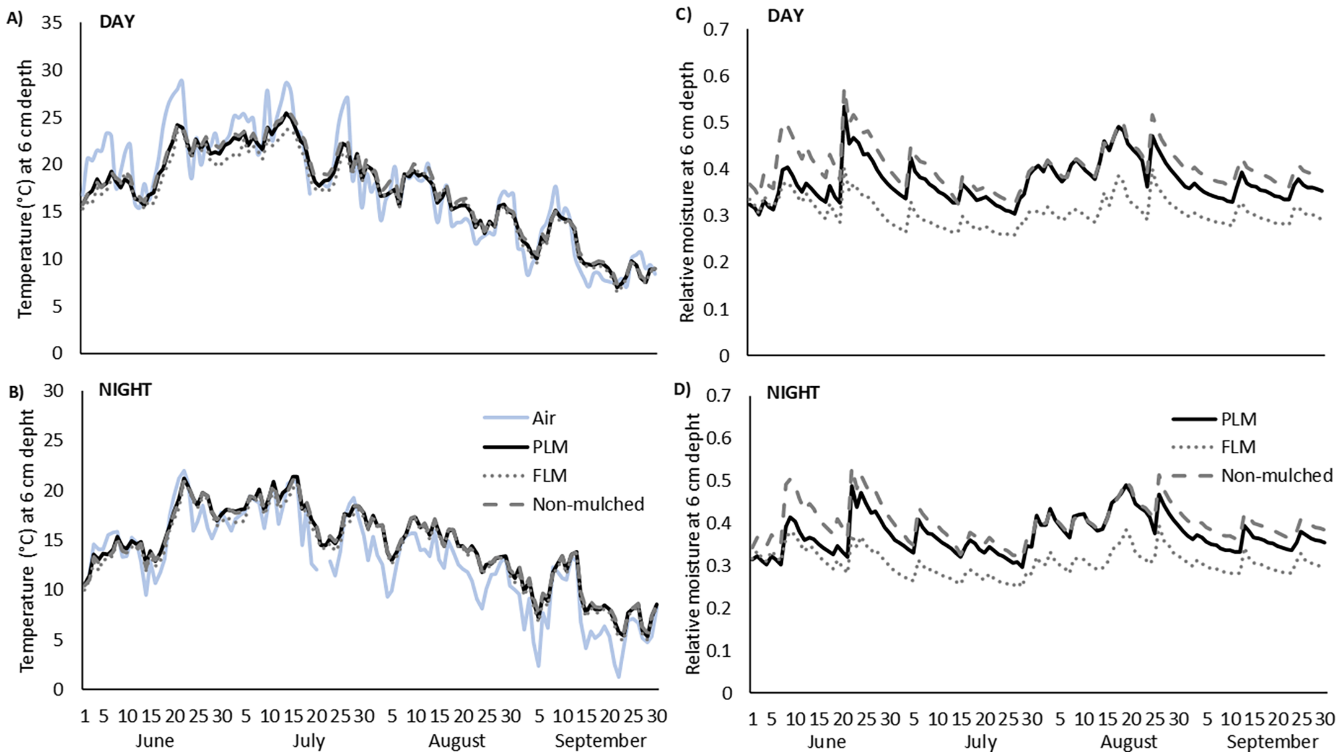

FIGURE 4 | Mean day and nighttime temperatures (A, B) and relative moisture content (C, D) in the soil at 6 cm beneath peat (PLM) and fibre (FLM)-based mulches containing pyrolysis liquid and in the non-mulched soils without mulching during the first growing season (2021). The air temperature (light blue line) was recorded at the nearest climate station in Somero (distance c. 50 km).

the FLM treatment was 14 cm shorter and those grown in the PLM treatment 12 cm taller than in the non-mulched treatment (Table 4).

Only a few seedlings died during the first growing period in 2021, three spruce in the FLM and two pine in the PLM treatments, with no significant differences in survival between the treatments ($p > 0.05$). No seedlings died in 2022 or 2023.

3.3 | Soil Temperature, Moisture and Properties

The mean daytime temperature beneath FLM was slightly lower (0.4°C–1.1°C) than in the non-mulched soil ($p = 0.0102$) (Figure 4). A similar trend was also observed in the mean nighttime soil temperature, but the difference with the non-mulched was not statistically significant ($p > 0.05$). Relative moisture content was lower beneath FLM than non-mulched soil, both in daytime ($p = 0.0383$) and nighttime ($p = 0.0365$). In contrast, the differences between PLM and FLM in temperature or relative moisture were not statistically significant ($p > 0.05$). Neither PLM nor FLM affected soil pH or EC at four or 12 weeks after mulching (Table 5).

3.4 | Estimation of Techno-Economic Performance

Material, manufacturing and application costs of the liquid mulch are €0.55, 0.56 and 0.31/m^2 respectively, resulting in a total of €1.42/m^2 for an application area of 100 m^2 (Table 6). The results represent preparing one 2 m^3 batch of mulch sufficient for application on an area of 100 m^2. The price of liquid mulch is €70.75/m^3, and due to assumed fast and easy spreading on a flat surface, the work cost is only €15.28/m^3.

The share of the different cost categories of the total FLM costs is presented in Figure S1 illustrating which cost categories have the most important economic effect on the FLM cost. The total cost of the FLM solution was mainly driven by manual labour (36%), followed by equipment (25%), with smaller contributions from transport (20%) and materials (19%) (Figure S4).

TABLE 5 | Mean (±SE) pH and EC of non-mulched soil and in the soil beneath PLM (peat, water and pyrolysis liquid) and FLM (fibre sludge, water and pyrolysis liquid) at 4 and 12 weeks after mulching ($n = 4$).

		EC, mS/m		pH	
Soil 4 weeks	PLM	18.1	±0.92 a	4.7	±0.59 a
	FLM	16.6	±2.02 a	5.0	±0.80 a
	Non-mulched	14.8	±2.16 a	5.0	±0.43 a
Soil 12 weeks	PLM	7.78	±0.91 a	5.0	±0.74 a
	FLM	7.78	±1.25 a	5.1	±0.38 a
	Non-mulched	10.2	±0.48 a	5.2	±1.68 a

Note: Within each column and sampling time, treatments with different letters are significantly different ($p < 0.05$).

TABLE 6 | Material, manufacturing and application costs of liquid mulch (2 m^3 for covering area of 100 m^2) containing pyrolysis liquid (PL) and fibre sludge (FLM).

Material costs

	Cost, €/m^3	*V*, m^3	Cost, €	Transport cost, €/h[a]	Distance, km	Cargo, m^3	Time, h	Transport cost, €	Total, €
Fibre sludge	0.00	0.60	0.00	62.44	400	137	7.25	3.30	3.30
PL	300.00	0.08	24.00	62.44	400	18	7.25	24.76	48.76
Water	2.52	1.32	3.33	—	—		—	—	3.33
Total	—	2.00	27.33	—	800	—	14.50	28.06	55.38

Manufacturing costs

	Amount, kg	*V*, m^3	Tractor cost, €/h	Employee cost, €/h	Pump cost, €/d	Pump power, kW	Time, h	Electricity cost, €/kWh	Total, €
FLM	1718	2.00	5.00	25.46	25.00	0.90	1.00	0.11	55.56

Application costs

	Amount, kg	*V*, m^3	Area, m^2	Tractor cost, €/h	Employee cost, €/h	Pump power, kW	Time, h	Electricity cost, €/kWh	Total, €
FLM	1718	2.00	100	5.00	25.46	0.90	1.00	0.11	30.56

Gross total

FLM price for 100 m^2, €	141.50
FLM price for one m^2, €	1.42

Note: Details for determining the material, equipment, utilities and employee costs, as well as the manufacturing and application methods, can be found in Section 2.
[a]Uotila et al. (2025). It is assumed that large amounts of FLM raw materials are stored near the manufacturing site; hence, when supplied for example once a year, the fibre sludge is transported with a truck as cargo of 137 m^3 (48 t). If this was 1 year's fibre material need, according to the recipe, the respective figure for PL would be 18.3 m^3 (20.7 t), which is therefore used as the cargo figure for PL.

4 | Discussion

4.1 | Weed Suppression Performance of Mulches

Both mulches prevented weed growth completely during the first 6 weeks after application. Twelve weeks after mulching, the number of weeds in PLM was 1.9 and in FLM 3.3 times (46%–70%) lower than in the non-mulched plots. The results are in line with Marble et al. (2019), who showed 71%–91% reductions in weed weight when using a 5 cm layer of pine bark, paper slurry and pine bark and crushed hardwood chips as organic mulches in a container nursery. In northern growing conditions, weed emergence is concentrated within a relatively short period in early summer. Therefore, the two assessment time points (6 and 12 weeks after mulching) capture the most critical phase of weed establishment in tree nurseries. The observed > 70% reduction in weed numbers indicates that fibre-based mulches could reduce the need for manual weeding during this period. Although polyethylene mulch was not included as a control in this study, its weed suppression efficiency is widely recognised to be high. Compared with polyethylene, biodegradable mulches typically provide somewhat lower but still substantial weed control, depending on material properties and environmental conditions.

The weed control effect of the tested mulches is likely based on the combined effect of the herbicidal properties of pyrolysis liquid, the inhibition of weed seed germination through light exclusion and the formation of a physical barrier restricting plant emergence and growth. Pyrolysis liquid contains several organic compounds with known herbicidal effects, such as acetic acid, propanoic acid, formic acid, furfural and some phenols (Yatagai et al. 2002; Hagner, Tiilikkala, et al. 2020). In addition, upon drying, the mulch forms a physical hard surface layer, preventing seedlings from breaking through the mulch cover (Hagner, Hyvönen, et al. 2020). Similar mechanisms have been reported for cellulose-based and hydromulch systems, showing suppressed weed germination and growth because of the formation of a protective and sunlight-blocking layer on the soil surface, thus reducing competition between the desired plants and weeds (Benoit et al. 2006; Riseh 2024). In addition to weed suppression, mulch layers may also influence soil temperature dynamics and surface processes, as shown in previous hydromulch studies (O'Brien et al. 2018; Ricks et al. 2020).

However, complete weed suppression was not achieved, and species-specific differences in response were observed. In the present study, wind-dispersed species such as *Senecio vulgaris* and *Taraxacum officinale* were among the most abundant taxa, suggesting colonisation from surrounding areas. These species may germinate on the mulch surface after application, a phenomenon also observed in hydromulch studies (e.g., Cirujeda et al. 2024). Differences in species responses were also evident, as previously observed for species with strong root systems (Hagner, Lindqvist, et al. 2020). The relatively good control of *T. officinale* in this study may be explained by establishment from seed in newly prepared growing media. Overall, these results indicate that the effectiveness of liquid mulches depends on both material properties and weed functional traits. Additional testing is therefore required under diverse field conditions to optimise application rate and liquid mulch composition.

4.2 | Effects of Mulches on Tree Seedlings

Neither FLM nor PLM affected the survival of tree seedlings but treatment effects on seedling growth were observed. No significant effects of mulching on pine growth were detected. In contrast, PLM increased the growth of birch and spruce, while FLM reduced the growth of birch and no effect was observed in spruce. The reason for reduced birch growth may be related to the lower moisture content beneath FLM (see Section 4.3). If water scarcity contributed to the slower growth of birch seedlings, this effect could be mitigated by drip irrigation or adjusting the irrigation rate. In some conditions, both biodegradable and non-biodegradable mulches may have some negative effects on plant metabolism, photosynthesis and yield (Liwarska-Bizukojc 2022; Ren et al. 2022). The increased growth observed in PLM grown seedlings may be explained by several interacting factors. First, reduced weed competition likely improved the availability of water and nutrients for seedlings. Second, the mulch layer may have contributed to a more favourable microclimate by moderating soil temperature and reducing evaporation. Similar effects of mulching materials on soil temperature and hydrothermal conditions have been reported in previous studies (e.g., Moreno et al. 2016; Wang et al. 2019), supporting the interpretation of the observed microclimatic effects in the present study.

Previously, we found that a 2-week stabilisation period was required between mulching and planting with grassy species when using PLM (Hagner, Hyvönen, et al. 2020). Although plants with woody stems are probably more tolerant, we also used a 2-week stabilisation period in the present study. However, if mulches were in direct contact with the base of 4- to 5-year-old tree seedlings, the seedlings' survival was unaffected. This finding simplifies and expands the usability of PLM/FLM, as no stabilisation period is required, nor does the base of older seedlings need to be protected when mulches are being spread. As a biodegradable material derived from organic feedstocks, these mulching solutions may also have the potential to be used in organic farming, where the need for alternative weed control methods is even more urgent than in conventional farming or nurseries. However, it should be noted that these observations are based on relatively mature seedlings (3–5 years old), and younger seedlings may be more sensitive to the physical or chemical effects of the mulching materials. Therefore, caution is needed when generalising these results to earlier developmental stages.

4.3 | The Effect of Mulches on Soil Parameters

The temperature beneath FLM was slightly lower (0.4°C–1.1°C) than PLM and in the non-mulched soil, probably because of the lighter colour of the mulching material than with dark soil and peat-based PLM (see Figure S1). Previously, the colour of mulch films has been shown to play a role in altering soil properties: black mulch films have been shown to increase the soil temperature, facilitate nutrient absorption into plant roots (Kader et al. 2017) and maintain soil moisture (Gao et al. 2019). Similar effects of biodegradable mulch materials on soil temperature have been reported by Moreno et al. (2016), who showed that mulch type and material properties modified soil thermal conditions in tomato (*Lycopersicon esculentum* Mill.) field. In climatic areas where an increase of soil temperature is desired, black pigment biochar, for example, can be added to the mulch to attain similar beneficial effects to conventional plastic mulch films (Adhikari et al. 2019) (Figure S5). However, mulches with a lighter colour may be beneficial on growing sites suffering from extended periods of hot weather and high evaporation. Overall, the possibility of modifying the colour of mulch with additives can be considered an asset that increases the versatility of sites where mulches can be used.

The relative moisture content of the growing substrate was lower beneath FLM mulch than the non-mulched soil, but no significant difference was detected between the two mulches or between PLM and the non-mulched treatment. Recently, El-Beltagi et al. (2022) concluded in their review of the benefits of organic mulches in soil and water conservation that organic mulches promoted moisture retention, allowing crops to access adequate water, especially in challenging climates or during droughts. Cellulose has amorphous domains that enable flexibility and interactions with water molecules, which makes it a suitable material for absorbing and retaining soil moisture (Etale et al. 2023). However, increased hydrophobicity of mulching material during drying (practical observation) may influence water movement through the mulch layer, which requires further study. In the present study, artificial irrigation probably penetrated the PLM treatment through visually observed cracks in the mulch surface, which may also partly explain the larger number of weeds in the PLM treatment, and the lack of difference in soil moisture between PLM and non-mulched soil. Regarding irrigation, an interesting further study question is the use of drip irrigation beneath the mulches, especially in dry climates or for crops with high water demand during the growing season (e.g., tomato) as also explored in previous field studies with biodegradable films and hydromulches (Cirujeda et al. 2024; Wang et al. 2019).

4.4 | Techno-Economic Performance Estimation

Despite efforts to ensure realistic assumptions, the techno-economic estimation in this study entails unavoidable simplifications and uncertainties. Comparable agronomic and economic analyses of biodegradable mulch systems have been reported in previous studies (e.g., Anzalone et al. 2010; Burato et al. 2025), indicating that their performance and cost-effectiveness depend strongly on-site conditions, crop type and management practices. In the present study, the total estimated cost of FLM application was €141.50 per 100 m^2, corresponding to €1.42 m^{-2}. Our results shows clearly that manual labour constitutes the largest share of the total FLM costs: its share is 36%, followed by equipment, transport and materials, respectively.

The cost estimates are affected particularly by uncertainties related to raw material markets and logistics. The market for PL is still immature, and its price may vary depending on feedstock, production temperature, product purity and acid concentration. In the EU, the lack of required REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals; European Union 2006) registration limits the markets for PL. However, as the portion of the PL in FLM formulation is small, changes in its price have only a moderate effect on the final product cost. Fibre sludge was assumed to have no purchase price, and transport was therefore the main cost associated with this raw material. Detailed assumptions used in the cost calculation are provided in Table 6 and Supporting Information.

Compared with manual weeding, the estimated cost of FLM appears competitive, particularly when weed pressure is high and hand weeding must be repeated several times during the growing season. Manual weeding costs are strongly affected by weed abundance and labour requirements. For comparison, the cost of manual weed removal can reach several thousand euros per hectare (Case et al. 2005), and cost naturally increases if the work has to be repeated (Figures S6 and S7). In this context, the estimated cost of €141.50 per 100 m^2 for the FLM solution seems competitive, although a mid-term analysis is necessary. A conservative cost estimate for black polyethene plastic is only €0.50/m^2. As this non-biodegradable material needs to be removed after the growing season, the application cost can be estimated to be at least double that for applying FLM; the resulting cost for polyethene plastic mulch is therefore roughly €0.50/m^2 + 2 × €0.31/m^2 = €1.12/m^2.

Compared with other biodegradable mulching materials, such as biodegradable plastics, fabrics, or non-wovens, the estimated FLM cost falls within the same order of magnitude. These materials have been estimated to be two to four times more expensive than polyethylene mulch, corresponding to approximately €1.31–2.31 m^{-2} when application costs are assumed to be similar to those of FLM. In addition, FLM can be applied to areas of irregular shape without the need for cutting or fitting the material, unlike conventional mulch films. Overall, the key to improving FLM's economic feasibility is to reduce manual labour and improve the efficiency of manufacturing and application methods.

5 | Conclusions

The two biodegradable liquid mulch solutions consisting of either peat or pulp and a paper by-products and pyrolysis liquid showed a reduction in weed emergence over a 3-month monitoring period. The solution based on recycled industrial by-product materials (FLM) was more effective against weeds in the tree nursery than the solution based on peat. It is however necessary to explore the weed control capacity of these mulches during a longer period. No adverse effects on seedling growth were observed in pine and spruce, but birch, exhibiting the most vigorous growth and intensive water uptake, showed reduced growth under the FLM. Although both mulches allowed infiltration, the soil beneath FLM was drier. Further studies of drip irrigation beneath the mulch layer are therefore recommended, especially in dry and hot environments, where evaporation is high. The results also suggest that further development focusing on additives increasing durability against cracking and manipulating the colour of the mulches are recommended. In the tested Northern conditions dark colour increasing soil temperature can be considered beneficial whereas in warmer climates light coloured mulches capable to lower soil temperature is desired. Improved properties with biobased additives could allow thinner mulch layer, thereby reducing materials and transport costs. The estimated costs of FLM utilisation are higher than polyethene plastic film mulch; however, as polyethene is fossil-based and non-biodegradable, its sustainability is highly questionable. The techno-economic performance of FLM may be lower than repeated manual weeding, and appears to be within the range of current biodegradable mulching alternatives. Currently, the markets for FLM raw materials are undeveloped, and the price of PL especially is uncertain, which makes predicting exact FLM costs challenging. Nevertheless, the preliminary techno-economic analysis shows promising results, especially as the manufacturing and application technologies for FLM are expected to become more efficient and cost-effective in the future.

Acknowledgements

This study was funded by the Finnish Ministry of Education and Culture through the Bioproduct and Clean Bioeconomy—an RDI FlagShip at Xamk, and later (2023–2025), the PlastLIFE project (LIFE21-IPE-FI-PlastLIFE/101069513), mainly funded by the EU LIFE Programme. We thank the Haapastensyrjä and Jokioinen technical personnel, especially Ari Eskola, for their help with establishing and maintaining the experiment. Thanks to Juha Hyvönen and Jouni Karhu for their statistical help. Open access publishing facilitated by Luonnonvarakeskus, as part of the Wiley - FinELib agreement.

Funding

This work was supported by the Finnish Ministry of Education and Culture and European Union LIFE Programme (101069513).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Peer Review

For transparency, the peer review documents associated with this article are available at https://doi.org/10.1111/wre.70107.

References

Adhikari, R., H. Mingtarja, G. Freischmidt, et al. 2019. "Effect of Viscosity Modifiers on Soil Wicking and Physico-Mechanical Properties of a Polyurethane Based Sprayable Biodegradable Polymer Membrane." *Agricultural Water Management* 222: 346–353. https://doi.org/10.1016/j.agwat.2019.05.020.

Alexander, P. D., N. C. Bragg, R. Meade, G. Padelopoulos, and O. Watts. 2008. "Peat in Horticulture and Conservation: The UK Response to a Changing World." *Mires and Peat* 3: 8. http://www.mires-and-peat.net/pages/volumes/map03/map0308.php.

Anzalone, A., A. Cirujeda, J. Aibar, G. Pardo, and C. Zaragoza. 2010. "Effect of Biodegradable Mulch Materials on Weed Control in Processing Tomatoes." *Weed Technology* 24: 369–377. https://doi.org/10.1614/WT-09-020.1.

Bajwa, A. A., G. Mahajan, and B. S. Chauhan. 2015. "Nonconventional Weed Management Strategies for Modern Agriculture." *Weed Science* 63: 723–747. https://doi.org/10.1614/WS-D-15-00064.1.

Benoit, D. L., C. Vincent, and G. Chouinard. 2006. "Management of Weeds, Apple Sawfly (*Hoplocampa testudinea* Klug) and Plum Curculio (*Conotrachelus nenuphar* Herbst) With Cellulose Sheeting." *Crop Protection* 25: 331–337. https://doi.org/10.1016/j.cropro.2005.05.006.

Briassoulis, D., and A. Giannoulis. 2018. "Evaluation of the Functionality of Bio-Based Plastic Mulching Films." *Polymer Testing* 67: 99–109. https://doi.org/10.1016/j.polymertesting.2018.02.019.

Burato, A., D. Fichera, S. Cornali, R. Reggiani, and D. Ronga. 2025. "Soil-Biodegradable Mulching Films Improve Yield, Water Productivity, and Profitability in Organic Processing Tomato." *Italian Journal of Agronomy* 20: 00035. https://doi.org/10.1016/j.ijagro.2025.100035.

Case, L. T., H. M. Mathers, and A. F. Senesac. 2005. "A Review of Weed Control Practices in Container Nurseries." *HortTechnology* 15: 535–545. https://doi.org/10.21273/HORTTECH.15.3.0535.

Cirujeda, A., A. Anzalone, J. Aibar, M. M. Moreno, and C. Zaragoza. 2012. "Purple Nutsedge (*Cyperus rotundus* L.) Control With Paper Mulch in Processing Tomato." *Crop Protection* 39: 66–71. https://doi.org/10.1016/j.cropro.2012.03.028.

Cirujeda, A., J. Pueyo, M. M. Moreno, et al. 2024. "Weed Control in Perennial Crops Using Hydromulch Compositions Based on the Circular Economy: Field Trial Results." *Journal of Crop Health* 76: 1101–1116. https://doi.org/10.1007/s10343-024-01012-9.

Data Insights Market. 2025. *Industrial Round Wood Market 2025–2033 Analysis: Trends, Competitor Dynamics, and Growth Opportunities*, 180. PRDUA Research & Media Private Limited. https://www.datainsightsmarket.com/reports/industrial-round-wood-market-289.

Durado, A., D. S. Bajwa, G. Gramig, et al. 2024. "Biodegradable Composite Hydromulches for Sustainable Organic Horticulture." *Industrial Crops and Products* 221: 119349. https://doi.org/10.1016/j.indcrop.2024.119349.

El-Beltagi, H. S., A. Basit, H. I. Mohamed, et al. 2022. "Mulching as a Sustainable Water and Soil Saving Practice in Agriculture: A Review." *Agronomy* 12: 1881. https://doi.org/10.3390/agronomy12081881.

Etale, A., A. J. Onyianta, S. R. Turner, and S. J. Eichhorn. 2023. "Cellulose: A Review of Water Interactions, Applications in Composites, and Water Treatment." *Chemical Reviews* 123: 2016–2048. https://doi.org/10.1021/acs.chemrev.2c00477.

European Union. 2006. "Regulation (EC) No. 1907/2006 Establishes the 'REACH' (Registration, Evaluation, Authorisation and Restriction of Chemicals) System. It Aims to Protect Human Health and the Environment by Ensuring Greater Safety in the Production and Use of Chemical Substances." https://eur-lex.europa.eu/EN/legal-content/glossary/reach-regulatory-framework-for-chemicals.html.

Fagernäs, L., E. Kuoppala, K. Tiilikkala, and A. Oasmaa. 2012. "Chemical Composition of Birch Wood Slow Pyrolysis Products." *Energy & Fuels* 26: 1275–1283. https://doi.org/10.1021/ef2018836.

Faubert, P., S. Barnabe, S. Bouchard, R. Cote, and C. Villeneuve. 2016. "Pulp and Paper Mill Sludge Management Practices: What are the Challenges to Assess the Impacts on Greenhouse Gas Emissions?" *Resources, Conservation and Recycling* 108: 107–133. https://doi.org/10.1016/j.resconrec.2016.01.007.

Fennimore, S. A., and D. J. Doohan. 2008. "The Challenges of Specialty Crop Weed Control, Future Directions." *Weed Technology* 22: 364–372. https://doi.org/10.1614/WT-07-102.1.

Finnish Meteorological Institute. 2021. "Finnish Meteorological Institute Open Data Service." https://en.ilmatieteenlaitos.fi/open-data.

Gao, H., C. Yan, Q. Liu, W. Ding, B. Chen, and Z. Li. 2019. "Effects of Plastic Mulching and Plastic Residue on Agricultural Production: A Meta-Analysis." *Science of the Total Environment* 651: 484–492. https://doi.org/10.1016/j.scitotenv.2018.09.105.

Goldberger, J. R., R. Emmet Jones, C. A. Miles, R. W. Wallace, and D. A. Inglis. 2013. "Barriers and Bridges to the Adoption of Biodegradable Plastic Mulches for US Specialty Crop Production." *Renewable*

Agriculture and Food Systems 30: 143–153. https://doi.org/10.1017/S1742170513000276.

Haapala, T., P. Palonen, A. Korpela, and J. Ahokas. 2014. "Feasibility of Paper Mulches in Crop Production: A Review." *Agricultural and Food Science* 23: 60–79. https://doi.org/10.23986/afsci.8542.

Hagner, M., T. Hyvönen, J. Mikola, et al. 2020. "Efficiency of a Novel Biodegradable Pyrolysis Liquid-Amended Mulch in Weed Control." *Weed Research* 60: 182–193. https://doi.org/10.1111/wre.12411.

Hagner, M., B. Lindqvist, J. Vepsäläinen, et al. 2020. "Potential of Pyrolysis Liquids to Control the Environmental Weed *Heracleum mantegazzianum*." *Environmental Technology & Innovation* 20: 101154. https://doi.org/10.1016/j.eti.2020.101154.

Hagner, M., M. Räty, J. Nikama, et al. 2021. "Slow Pyrolysis Liquid in Reducing NH3 Emissions From Cattle Slurry—Impacts on Plant Growth and Soil Organisms." *Science of the Total Environment* 784: 147139. https://doi.org/10.1016/j.scitotenv.2021.147139.

Hagner, M., K. Tiilikkala, I. Lindqvist, et al. 2020. "Performance of Liquids From Slow Pyrolysis and Hydrothermal Carbonization in Plant Protection." *Waste and Biomass Valorization* 11: 1005–1016. https://doi.org/10.1007/s12649-018-00545-1.

Harker, K. N., and J. T. O'Donovan. 2013. "Recent Weed Control, Weed Management, and Integrated Weed Management." *Weed Technology* 27: 1–11. https://doi.org/10.1614/WT-D-12-00109.1.

Heap, I. 2026. "International Herbicide-Resistant Weed Database." https://www.weedscience.org/Home.aspx.

Kader, M. A., M. Senge, M. A. Mojid, and K. Ito. 2017. "Recent Advances in Mulching Materials and Methods for Modifying Soil Environment." *Soil and Tillage Research* 168: 155–166. https://doi.org/10.1016/j.still.2017.01.001.

Kasirajan, S., and M. Ngouajio. 2012. "Polyethylene and Biodegradable Mulches for Agricultural Applications: A Review." *Agronomy for Sustainable Development* 32: 501–529. https://doi.org/10.1007/s13593-011-0068-3.

Kern, J., P. Tammeorg, M. Shanskiy, et al. 2017. "Synergistic Use of Peat and Charred Material in Growing Media—An Option to Reduce the Pressure on Peatlands?" *Journal of Environmental Engineering and Landscape Management* 25: 160–174. https://doi.org/10.3846/16486897.2017.1284665.

Liu, E., L. Zhang, W. Dong, and C. Yan. 2021. "Biodegradable Plastic Mulch Films in Agriculture: Feasibility and Challenges." *Environmental Research Letters* 16: 011004. https://doi.org/10.1088/1748-9326/abd211.

Liwarska-Bizukojc, E. 2022. "Phytotoxicity Assessment of Biodegradable and Non-Biodegradable Plastics Using Seed Germination and Early Growth Tests." *Chemosphere* 289: 133132. https://doi.org/10.1016/j.chemosphere.2021.133132.

Marble, S. C., S. T. Steed, D. Saha, and Y. Khamare. 2019. "On-Farm Evaluations of Wood-Derived, Waste Paper, and Plastic Mulch Materials for Weed Control in Florida Container Nurseries." *HortTechnology* 29: 866–873. https://doi.org/10.21273/HORTTECH04437-19.

Monte, M. C., E. Fuente, A. Blanco, and C. Negro. 2009. "Waste Management From Pulp and Paper Production in the European Union." *Waste Management* 29: 293–308. https://doi.org/10.1016/j.wasman.2008.02.002.

Moreno, M. M., A. Cirujeda, J. Aibar, and C. Moreno. 2016. "Soil Thermal and Productive Responses of Biodegradable Mulch Materials in a Processing Tomato (*Lycopersicon esculentum* Mill.) Crop." *Soil Research* 54: 207–215. https://doi.org/10.1071/SR15065Marb.

O'Brien, P. L., U. Acharya, R. Alghamdi, et al. 2018. "Hydromulch Application to Bare Soil: Soil Temperature Dynamics and Evaporative Fluxes." *Agricultural & Environmental Letters* 3: 180014. https://doi.org/10.2134/ael2018.03.0014.

Peterson, M. A., A. Collavo, R. Ovejero, V. Shivrain, and M. J. Walsh. 2018. "The Challenge of Herbicide Resistance Around the World: A Current Summary." *Pest Management Science* 74: 2246–2259. https://doi.org/10.1002/ps.4821.

Rasa, K., T. Pennanen, K. Peltoniemi, et al. 2021. "Pulp and Paper Mill Sludges Decrease Soil Erodibility." *Journal of Environmental Quality* 50: 172–184. https://doi.org/10.1002/jeq2.20170.

Ren, X., L. Wang, J. Tang, H. Sun, and J. P. Giesy. 2022. "Combined Effects of Degradable Film Fragments and Micro/Nanoplastics on Growth of Wheat Seedling and Rhizosphere Microbes." *Environmental Pollution* 294: 118516. https://doi.org/10.1016/J.ENVPOL.2021.118516.

Ricks, M. D., W. T. Wilson, W. C. Zech, X. Fang, and W. N. Donald. 2020. "Evaluation of Hydromulches as an Erosion Control Measure Using Laboratory-Scale Experiments." *Water* 12, no. 2: 515. https://doi.org/10.3390/w12020515.

Riseh, R. S. 2024. "Review: Advancing Agriculture Through Bioresource Technology: The Role of Cellulose-Based Biodegradable Mulches." *International Journal of Biological Macromolecules* 255: 128006. https://doi.org/10.1016/j.ijbiomac.2023.128006.

StatFin. 2024. "Statistics Finland, Structure of Earnings. Total Earnings by Employer Sector, 2023." https://stat.fi/tup/suoluk/suoluk_palkat_en.html#Total%20earnings%20by%20employer%20sector.

StatFin. 2025. "Statistics Finland's Free-of-Charge Statistical Databases. 13rb–Price of Electricity by Type of Consumer, 2008M01-2025M03." https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__ehi/statfin_ehi_pxt_13rb.px/.

Stewart, C. J., S. C. Marble, B. J. Pearson, and P. C. Wilson. 2017. "Impact of Container Nursery Production Practices on Weed Growth and Herbicide Performance." *HortScience* 52: 1593–1600. https://doi.org/10.21273/HORTSCI12241-17.

Suomi.fi. 2025. "Digital and Population Data Services Agency." https://www.suomi.fi/guides/recruiting-an-employee/plan-the-recruitment/calculate-the-costs-of-the-employee#salary-costs-and-employer-s-indirect-costs.

Uotila, K., K. Vikki, M. Uusitalo, K. Rasa, I. Leinonen, and M. Hagner. 2025. "Mobile-Manufactured Biochar in Mine Closure, Costly Yet Carbon-Negative—A Techno-Economic and Life Cycle Assessment of Growing Media Value Chains." *Cleaner and Circular Bioeconomy* 12: 100173. https://doi.org/10.1016/j.clcb.2025.100173.

Wang, Z., Q. Wu, B. Fan, et al. 2019. "Effects of Mulching Biodegradable Films Under Drip Irrigation on Soil Hydrothermal Conditions and Cotton (*Gossypium hirsutum* L.) Yield." *Agricultural Water Management* 213: 477–485. https://doi.org/10.1016/j.agwat.2018.10.036.

Warnick, J. P., C. A. Chase, E. N. Rosskopf, et al. 2006. "Weed Suppression With Hydramulch, a Biodegradable Liquid Paper Mulch in Development." *Renewable Agriculture and Food Systems* 21: 216–223. https://doi.org/10.1079/RAF2006154West.

Water News Europe. 2021. "Water Prices Compared in 36 EU-Cities." *Water News Europe*, 19 March 2021. https://www.waternewseurope.com/water-prices-compared-in-36-eu-cities/.

Westwood, J. H., R. Charudattan, S. O. Duke, et al. 2018. "Weed Management in 2050: Perspectives on the Future of Weed Science." *Weed Science* 66: 275–285. https://doi.org/10.1017/wsc.2017.78.

Wild, J., M. Kopecký, M. Macek, M. Šanda, J. Jankovec, and T. Haase. 2019. "Climate at Ecologically Relevant Scales: A New Temperature and Soil Moisture Logger for Long-Term Microclimate Measurement." *Agricultural and Forest Meteorology* 268: 40–47. https://doi.org/10.1016/j.agrformet.2018.12.018.

Yatagai, M., M. Nishimoto, K. Hori, T. Ohira, and A. Shibata. 2002. "Termiticidal Activity of Wood Vinegar, Its Components and Their Homologues." *Journal of Wood Science* 48: 338–342. https://doi.org/10.1007/BF00831357.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** A prototype of a device used to spread mulch material. One hundred litre bucket, destructive submersible pump and drainpipe (left). Spreading head/splash pan (right). **Figure S2:** Experimental setup consisted of three treatments: (a) peat or (b) fibre sludge based liquid mulch applied with pyrolysis liquid; or (c) non-mulched plots, each having four replicates. Each experimental plot included seedlings of three tree species: pine; spruce; and birch. Pictures taken 2 weeks after mulching soon after the planting of seedlings. **Figure S3:** Reapplication of mulches was conducted at the beginning of the 2023 growing period, when tree seedlings were 3–4 years old, to determine whether direct contact with the mulches harmed older tree seedlings. **Figure S4:** Total costs of FLM categorised as material, transport, equipment and manual labour costs. Equipment costs include cost of electricity. The categories' percentage share is indicated in the figure after each category title. **Figure S5:** Fibre sludge (left) and peat (right) based liquid mulch materials on a petri dish. The advantage of fibre sludge based initially white mulch material is that natural dyes can be used to colour the material. For example, the addition of biochar results in a black mulch (bottom). **Figure S6:** Example area 1 used to estimate working time needed to remove weeds manually. **Figure S7:** Example area 2 used to estimate working time needed to remove weeds manually.