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Article

Influence of Sheep's Wool Vegetation Mats on the Plant Growth of Perennials

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Abstract: Vegetation mats for horticulture and landscaping usually consist of coconut fibre and straw. They have hardly any available nutrients and serve only as a carrier material for plant growth. Water capacity is low. By incorporating raw sheep's wool, nutrients, such as nitrogen, potassium, and sulphur can positively influence the nutrient content of the carrier material. Water storage and water holding capacity are increased by the wool. In this study, three different thick-layered vegetation mats with different proportions of sheep's wool and coir fibres were developed for the pre-cultivation of perennials. The focus is on the evaluation of sheep's wool as a carrier material compared to pure coconut fibre as well as the plant growth of the eight perennial species used (*Achillea clypeolata* 'Moonshine', *Achnatherum calamagrostis* 'Algäu', *Anaphalis triplinervis*, *Aster dumosus* 'Prof. Anton Kippenberg', *Aster dumosus* 'Silberball', *Centranthus ruber* 'Coccineus', *Coreopsis verticillata*, *Salvia nemorosa* 'Rosakönigin'). The vegetation mats with sheep's wool (V1–V3) contained 192.6, 154.0, and 283.5 g nitrogen (N)/m^2 and the coir mats (V4) contained 7.5 g N/m^2. The water content ranged from 16.0 to 22.1 vol% for the sheep's wool mats and 12.6 vol% for the coir mat at pF1 (is equal to matrix potential at −10 hPa). The air content ranged from 71.9 to 77.0 vol% for the sheep's wool mat and 79.4 vol% for the coir mat at pF1. On all vegetation mats containing sheep's wool, the overall impression of the perennials was better than in the control. Especially good were *Asters*. At the end of the trial, the assessment scores of *Asters* on the sheep's wool mats were two scores higher than on the coir mat. *Aster dumosus* 'Prof. Anton Kippenberg' achieved an average plant height between 35.8, 35.8, and 36.5 cm on the sheep's wool mats and 14.4 cm on the coir mat. *Aster dumosus* 'Silberball' yielded 41.3, 42.3, and 44 cm on the sheep's wool mats and 26.7 cm on the coir mat. No significant differences regarding plant height between the different variants of sheep's wool mats emerged. Therefore, these mats can be used as alternative planting concepts for landscaping.

Keywords: sheep's wool; coconut fibre; vegetation mat; perennials; pre-cultivation; fertiliser; urban horticulture

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1. Introduction

1.1. History of Vegetation Mats

Vegetation mats or erosion protection mats have been used in biological engineering since the 1970s [1–3]. They are mainly used in hydraulic and road construction and can protect slopes, banks, and embankments from erosion directly after installation [4–6]. The greening normally happens after placement using the hydroseeding technique [7].

Since the 1980s, pre-cultivated vegetation mats are increasingly used in extensive roof greenings. This offers the advantage of tackling greening challenges, e.g., providing light-weighted and thin-layered systems [4]. For pre-cultivation, the vegetation mats are scatter-coated with a thin layer of substrate and seeds or seedlings are inserted. Currently, mosses, *Sedum* species, grasses, and/or herbs are common plants in roof greening [4]. Once a total coverage of 75% is achieved, the vegetation mats can be installed [8].

Pre-cultivation of perennials can be carried out on vegetation supports similar to those used for extensive green roofs. This has been demonstrated by investigations of thin-layer, latexed coconut fibre mats [9]. If young plants are to be pre-cultivated on vegetation mats, thicker-layered coconut mats are chosen [10]. Some of the benefits of using pre-cultivated vegetation mats are an early high coverage ratio of ≥75% [8] and lower maintenance effort due to the mulch effect of the fibre mat, which decreases the emergence of weeds.

1.2. Deployment of Natural Fibres

Currently, in gardening and landscaping, vegetation mats are usually made of coconut fibres or rock wool. Considering climate change and the scarcity of resources, it is increasingly important to make use of environmentally friendly and sustainable materials [11]. The materials that are used in horticulture, such as coconut fibre, haven been proven to be a good carrier material [12], though they entail ecological and economic disadvantages. Coirs are not produced in Germany and are, therefore, imported from Asia. Therefore, transport costs are high, and they are expected to increase further. In addition, the production process requires a large amount of water for cleaning the coconut fibres, which also makes the use of the fibres more expensive, as water will become an increasingly scarce resource in the future. Especially with regard to ecological sustainability, native organic and fully biodegradable substrates are gaining importance in horticulture [13]. Sheep's wool is a local and renewable resource that is often a waste material and it has come to the fore in gardening and landscaping services.

It is increasingly available, as it is being replaced more and more by synthetic fibres in the textile market. Furthermore, the last wool scouring facility in Germany was shut down in 2009 [14]. Raw wool processing is now outsourced to countries, such as Belgium, Italy, or Austria, which still operate those facilities. The number of sheep in Germany is continuously decreasing and reached its low in 2021 at 1.5 million sheep [15].

The global sheep population in 2020 was 1.26 billion [16]. On a global scale, the sheep population increased in the last years, where China accounts for a large share with approx. 173 million sheep. India, with a sheep population of 68 million, also expanded their amount in recent years. Together with China and Australia, these countries make up the largest share of sheep in the world [17]. Sheep's wool is mainly used in the textile industry in China and India [18].

Due to the high compatibility between fabric properties and the physiological requirements of plants, sheep's wool can be applied in horticulture without washing being a prerequisite. The coarse wool or the wool from the abdomen or the legs—or rather, the cast wool—are often residual materials, which makes them available for horticultural purposes. Raw wool contains important nutrients for plant physiology, such as nitrogen (10.4–10.7%), potassium (4.6–4.9%), and sulphur (2%) [19]. Phosphorus (0.1–0.2%) is only present in small quantities [19]. Sheep's wool has quite a high pH value: between 7.5 and 9 [20]. The maximum water capacity is more than triple the gross weight [21].

Innovations indicating the valuable material properties of raw sheep's wool concerning plant physiological requirements have been promoted since the 2000s. Product developments, such as thin-layered vegetation mats for horticultural purposes [22], are described in the utility model for "Vegetationsträger aus organischen verrottbaren Fasermaterialien" (translation: "Vegetation carrier made from organic and biodegradable fibre materials") [23]. The procedure stipulates shredding and, when appropriate, mixing the unpurified, hygienised, raw sheep's wool with coir. Subsequently, the thin-layered vegetation mat is fabricated with the aerodynamic layering of fleece. Additionally, the gardening and landscaping industry and horticulture are using vegetation systems involving sheep's wool that is manufactured with the Kemafil® Technology or as needled fleece [24–27]. The utilisation of local sheep's wool can consequently reduce the coir import and thereby decrease transport costs.

Several scientific investigations have found an advantageous fertilising effect of sheep's wool, resulting in enhanced plant growth in various cultures (ornamental plants, vegetables, herbs, cereals, and grasses) [20,28–37]. In most trials, raw sheep's wool was used as a fertiliser. The development and production of fertilisation pellets from sheep's wool [20,21], in conformity with the utility model of "Organisches Düngemittel" (translation: Organic fertiliser) [37], also supports the application of sheep's wool in horticulture. Furthermore, sheep's wool pellets can be used in agriculture to improve soil [29].

Within the framework of this research project, vegetation mats made of sheep's wool and coconut fibres are being developed and investigated with regard to the plant growth of perennials. There is a high demand for sustainable products in horticulture, and new distribution channels for sheep's wool are needed. In response to this, the goal of the present work was to use the developed vegetation mats to cultivate perennials and thereby promote alternative planting concepts for urban green, prospectively. According to horticultural practice, vegetation mats must be pre-cultivated before the relocation to the target area in public urban green. Therefore, the investigations in this study were performed during pre-cultivation.

The hypothesis implied that sheep's wool would be more suitable as a carrier material for vegetation mats than coconut fibre due to its advantageous nutrient composition and high water absorption capacity [19,21]. Through trials, the influence of the proportion of sheep's wool in vegetation mats on the plant growth of different perennial plants was evaluated and compared to conventional coir vegetation mats. Supplementarily, the chemical and physical properties of the utilised raw materials and their interaction with the plants' development are determined.

2. Materials and Methods

2.1. Utilised Sheep's Wool Vegetation Mats and Their Properties

The raw wool from Germany was hygienised according to a standard hygienisation procedure (EU-regulation Nr. 142/2011 [38]) before processing. After hygienisation, the wool was shredded with a machine specifically designed for raw wool.

The nitrogen content of the sheep's wool and the coir was analysed as a mixed sample with a triple repetition, as per the VDLUFA II.1, 3.5.2.7 (2000) method [39].

The production of the vegetation mats with the aerodynamic web forming was then carried out by MST-Dränbedarf GmbH (Twistringen, Germany). The processed fibres were air-dried. The vegetation mats were approximately 5 cm thick and were fabricated as a 1 m wide fleece coil (length approx. 10 m). Subsequently, they were cut into 1 m × 1 m squares. For sufficient stability, the 1 m^2 mats were reinforced with 400 g of coir fabric on both sides. Three different kinds of vegetation mats containing sheep's wool and coir were produced and examined.

The variant 1 (V1) and 2 (V2) mats consisted of mixed fibre fleeces. The mat of variant 3 (V3) consisted of two fibre fleeces with 100% sheep's wool and was covered with a mixed-fibre fleece containing 30% sheep's wool and 70% coir from below and above (i.e., sandwiched). The mat of variant 4 (V4) served as a control, consisted of a thick-layered fleece of 100% coir, and was likewise reinforced with coir fabric on top and below (Table 1).

Table 1. Composition of vegetation mats and their weight proportion of air-dry fibres.

Mat Variant	Composition of Fleece	Proportion Sheep's Wool (kg/m^2)	Proportion Coir (kg/m^2)	Total Weight (kg/m^2)
V1: 50sw/50c	50% sheep's wool and 50% coir	1.8	1.8	3.6
V2: 30sw/70c	30% sheep's wool and 70% coir	1.4	2.8	4.2
V3: Sandwich	30% sheep's wool and 70% coir, Core: 100% sheep's wool	2.7	0.9	3.6
V4: 100c (control)	100% coir	0.0	2.5	2.5

2.2. Physical Properties

The investigations of the maximum water capacity as a function of the suction tension were carried out in accordance with DIN EN 13041:2012-01 [40].

For sampling, 100 mL stainless steel sampling cylinders were filled to the top with the various fibre mixtures. The materials were analysed as shown in Table 1 after being air-dried initially.

For the determination of the maximum water capacity, the cylinders with the fibre samples were saturated with six-fold repetition for at least 24 h in water and then drained for five seconds on a filter fleece. The cylinders were then weighed.

The investigations of the maximum water capacity were carried out at pF values of 0.0; 0.4; 1.0; 1.5, 1.8, and 2.0 in the sandbox of Eijkelkamp (Giesbeek, Netherlands). Here, the dimensionless pF value (=log cm water column) describes the energy with which the soil water is held in the soil (substrate) against gravity [41]. Field capacity describes the amount of water that the soil can hold against gravity for two to three days and is determined at a pF value of 1.8 [42]. Air capacity was calculated as the difference between the volume of the cylinders, the amount of water taken up, and the volume taken up by the fibres at pF 1.0 [43].

After testing, the samples were dried at 105 °C until displaying weight constancy. Then, the dry mass of the fibres and the bulk density were determined. The bulk density of the sheep's wool at 1.32 g/cm^3 and that of the coconut fibre at 1.15 g/cm^3 were used for the calculations of fibre volume [44].

2.3. Experimental Conditions during Pre-Cultivation

Pre-cultivation of the vegetation mats was carried out at the experimental site of the Albrecht Daniel Thaer-Institute of the Humboldt-Universität zu Berlin in Berlin-Dahlem. The test site belongs to the northeast German lowlands and is located 51 m above sea level (geographical coordinates: 52°28′ N; 13°18′).

The prevailing temperate climate at the test site is characterized by the transition from the maritime to the continental climate zone due to its eastern location. Temperatures during the experimental period from June to October 2015 were, on average, 0.5 K higher than the 30-year mean (1981–2010). Precipitation was 84% of the 30-year mean. Global radiation in the experimental period was 2402 MJ/m^2 and was 12% higher than the 30-year mean [45].

2.4. Selection of Perennial Plants

The selected perennials have different nutrient requirements. The perennials were chosen so that the entire range of nutrient requirements of the perennials could be covered. The perennial mix also varied in plant height and flowering time. The aim was to investigate whether sheep wool, with its slow release of nutrients, is suitable for all perennials.

The young plants used for pre-cultivation were grown in P9 pots (0.5 L) and were supplied by the perennial nursery Lux-Staudenkulturen in Pirna (Germany). The plants showed a uniform growth pattern and height. Eight different perennial species were used for the sunny location following the perennial mixture "Veitshöchheimer Blütentraum" with double repetition per mat (1 m^2) (Table 2).

Table 2. Overview of the selected perennials for sunny positions and nutritional requirements.

Botanical Name	Nutritional Requirements [46]
Achillea clypeolata 'Moonshine'	low
Achnatherum calamagrostis 'Algäu'	low
Anaphalis triplinervis	low
Aster dumosus 'Prof. Anton Kippenberg'	high
Aster dumosus 'Silberball'	high
Centranthus ruber 'Coccineus'	low–middle
Coreopsis verticillata	middle
Salvia nemorosa 'Rosakönigin'	middle

2.5. Pre-Cultivation

Pre-cultivation was performed with six replicates from 10 June 2015 (Figure 1a) to 27 October 2015 (Figure 1b) for each mat. The 24 vegetation mats of 1 m^2 each were laid randomly on the experimental area. Subsequently, 16 planting holes were cut in each mat and eight perennials were planted in duplicate.

(**a**) (**b**)

Figure 1. Experimental arrangement of perennial mats: (**a**) start of pre-cultivation (June 2015) (**b**) end of pre-cultivation (October 2015).

2.6. Pre-Cultivation Conditions

Irrigation was initially carried out with an oscillating sprinkler from Gardena® (GARDENA Deutschland GmbH, Ulm, Germany) and, from July 2015, with an irrigation system(single-drip hoses) from Netafim™ (NETAFIM Deutschland GmbH Innovative Bewässerung, Frankfurt, Germany), irrigated twice a day with a total volume of 4 L/m^2, adjusted according to weather conditions and according to [47]. Each mat (1 m^2) received 50 mL of fertiliser dissolved in 5 L of irrigation water with 1.4 g of dissolved nitrogen weekly during the pre-cultivation period. A total of 28 g of nitrogen per m^2 was applied over the experimental period. The fertilised nitrogen was neglected in the analysis of the correlation between plant height and the nitrogen content of the mats.

2.7. Data Collection

The plants were assessed every 14 days from July to October 2015. Overall impressions and plant heights were recorded as indicators of vitality [48]. In the assessment, each individual plant was evaluated using subjective visual observation with regard to its overall impression. This was done by assigning scores taking into account the respective stage of development (grades: BN 1 = plant failure, BN 3 = sufficient, BN 5 = satisfactory, BN 7 = good, BN 9 = very good).

Plant height (stem height) was measured with a folding rule with a measuring accuracy of 0.5 cm.

In addition, the number of shoots and the flowers/buds of each perennial were recorded on all assessment dates, but these were not evaluated here due to the abundance of data.

2.8. Statistical Analysis

Statistical analyses were performed with SPSS (28.0). The median of the assessment scores was calculated, and the distribution of the values in relation to the mat varieties and the plants was determined. The plant height of the plants was evaluated in relation to the vegetation mat using analysis of variance (ANOVA) tests. Significant differences were calculated using Tukey's test at a significance level of $p < 0.05$, with different lowercase letters denoting significance. Mean variability was indicated by standard deviation, denoted by ± or by error bars.

The physical parameters of the vegetation mats were averaged, and the mean variability was labelled.

To detect interactions between the total nitrogen content of different vegetation mats and the plant height, linear correlations between two variables were calculated using Pearson correlation (r) with a significance level of $p < 0.05$. In addition, the correlation between water capacity at pF 1 and the plant height was calculated using Pearson correlations (r) with a significance level of $p < 0.05$.

3. Results and Discussion

3.1. Nitrogen Content of the Vegetation Mats

The analysis of total nitrogen showed 10.4% for the sheep's wool fibres and 0.3% for the coconut fibres. The subsequently calculated nitrogen content in the four vegetation mat types averaged between 7.5 g of nitrogen (variant 100c) and 283.5 g of nitrogen (sandwiched variant) per m^2 vegetation mat (Table 3).

Table 3. Calculated nitrogen content of the fibres (air dry) of the used vegetation mats.

Mat Variant	N-Content of Sheep's Wool Fibres in the Vegetation Mat (g/m^2)	N-Content of Coconut Fibre in the Vegetation Mat (g/m^2)	Total N-Content of Fibres in the Vegetation Mat (g/m^2)
V1: 50sw/50c	187.2	5.4	192.6
V2: 30sw/70c	145.6	8.4	154.0
V3: Sandwich	280.8	2.7	283.5
V4: 100c	0	7.5	7.5

3.2. Water Content

Depending on their origin, the water content of organic substrate constituents for growing media at a suction tension of pF 1.0 was between 8–12 vol% for coir fibres and between 67–83 vol% for raised bog peat, H6–8. The air content at matrix potential pF1 was between 83–90 vol% (coir fibres) and between 9–25 vol%. (Raised bog peat, H6–8) [49]. For peat, the degree of decomposition was given from H1 to H10 [50]. It provides information on the degree of decomposition of the peat-forming vegetation. H6–8 means that the degree of decomposition was strongly advanced (1/2 to 2/3 peat substance).

The investigations showed (Figure 2, Table 4), that the water content of coir was lowest at pF 0.0 with 59 vol% and at pF 1.0 with 13 vol%. The vegetation mats consisting of a mixture of sheep's wool and coir had a water content of 65–82 vol% at pF 0.0 and 16–22 vol% at pF 1.0. This was slightly higher than the water content of pure coir. The air content of the vegetation mats with sheep's wool was between 71.9 and 77.0 vol% at pF 1.0 and was 79.4 vol% for the coconut fibre mat.

All values were tested with Tukey's HSD test. Different small letters indicate significant differences ($p < 0.05$). In terms of water content and total pore volume, sheep's wool in combination with coconut fibre was a suitable growing medium. It absorbed more water than pure coconut fibre and retained it for a longer period of time, which is consistent with the results of [22]. It can be seen that, as the pF value (matrix potential) increased, the water content of the sandwich mat was always the highest compared to the other vegetation mats (Figure 2).

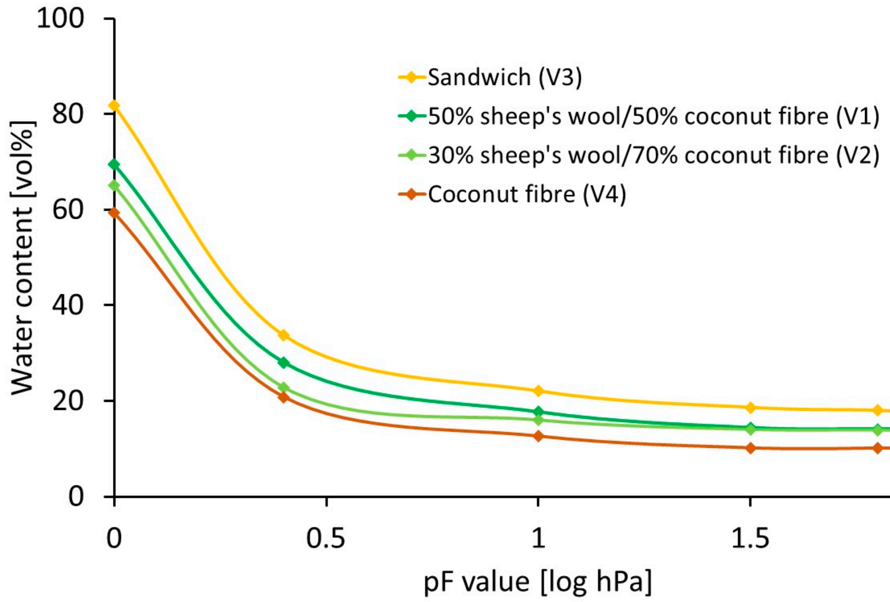


Figure 2. Influence of vegetation mats on the relationship between matrix potential and water content; V = variant of matte.

Table 4. Physical properties of substrates.

Substrate	Density (gcm^{-3})	Measured Bulk Density ($g\ 100\ cm^{-3}$)	Calculated Total Pore Volume (vol%)	Measured Water Content at pF0 (vol%)	Measured Water Content at pF1 (vol%)	Measured Air Content at pF1 (vol%)
V1: 50sw/50c	1.24	7.9 ± 0.05	93.6 ± 0.04	69.4 ± 1.51 b	17.6 ± 0.50 b	75.9 ± 0.47 b
V2: 30sw/70s	1.20	8.5 ± 0.03	93.0 ± 0.02	65.1 ± 1.41 b	16.0 ± 0.27 b	77.0 ± 0.28 b
V3: Sandwich	1.28	7.7 ± 0.02	93.9 ± 0.01	81.8 ± 1.10 c	22.1 ± 0.46 c	71.8 ± 0.45 a
V4: 100c	1.15	9.2 ± 0.01	92.0 ± 0.01	59.3 ± 0.98 a	12.6 ± 0.20 a	79.4 ± 0.19 c
Other substrate constituents			60–98 [49]	71.8–87.1 [51]	8–83 [49]	9–90 [49]

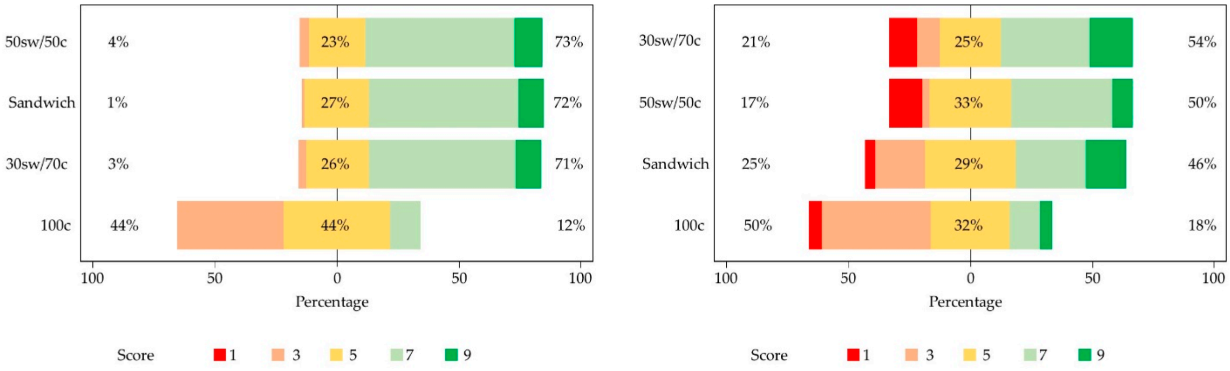
3.3. Overall Impression of the Perennials during Pre-Cultivation

As shown in Table 5, the median of the awarded scores of all perennials grown on vegetation mats with sheep's wool was "7" on the first assessment date, whereas the perennials grown on the coir mat yielded a score of "6". During the assessment period, the perennials developed well on all vegetation mats, although the scores of the perennials on the coconut fibre mats deteriorated towards the end of the vegetation period.

Table 5. Medians of the awarded scores of all perennials on the different vegetation mats on the 1st, 3rd, 5th, and 7th assessment dates.

Mat Variant	Score (1st Date)	Score (3rd date)	Score (5th Date)	Score (7th Date)
50sw/50c	7	7	7	5
30sw/70c	7	7	7	5
Sandwich	7	7	5	5
100c	6	7	5	4

The individual scores for the first evaluation showed (Figure 3a) that the selected perennials were able to establish themselves well immediately after planting on the vegetation mats with sheep wool. Scores of "7" and "9" were given much more often (between 71% and 73%) than on the coconut fibre mats (12%). A score of "5" was given to 23–27% of the perennials on the vegetation mats with sheep's wool, whereas 44% of the perennials (i.e., almost half of all perennials) received a score of "5" on the coconut fibre mat.



(**a**) (**b**)

Figure 3. Influence of vegetation mats on overall impression during the course of the trial; 1 = plant failure, 3 = sufficient, 5 = satisfactory, 7 = good, 9 = very good of (**a**) 1st date of evaluation (7 July 2015) and (**b**) 7th date of evaluation (29 September 2015).

A score of "3" was the highest awarded on the coconut fibre mat, with 44% signifying that pre-cultivation of the perennials was not optimal from the beginning. It became clear that the perennials could not develop optimally at the beginning of the pre-cultivation. On the other hand, the vegetation mats incorporating sheep's wool showed a very low proportion of plants with a score of "3" (1–4%).

In the further cultivation period, the vegetation mats with sheep's wool showed a slight deterioration of the overall impression. The seventh assessment at the end of September 2015 showed (Figure 3b) that scores of "9" and "7" on the vegetation mats with sheep's wool were significantly lower than in the first assessment (46–54%), whereas, on the coconut fibre mats, they increased somewhat (18%). A score of "5" was awarded to about a quarter to a third of all mats (25–33%). It was also noticeable that, at the end of the growing season, half of all perennials on the coconut fibre mats (50%) received a score of "1" or of "3", whereas, on the sheep's wool mats, this proportion was only between 17% and 25%.

The selected perennials were less suitable for pre-cultivation on coir mats than on sheep's wool mats. The better plant growth on the sheep's wool mats could be due to both the better water capacity of the sheep's wool and the high nitrogen content. These results correspond with those of an investigation of the pre-cultivation of sheep's wool vegetation mats for extensive roof greening [52].

Comparing the scores of the eight perennial species at the seventh assessment date at the end of September 2015, the following can be observed:

Plant failure was observed in 30% of *Achillea clypeolata* 'Moonshine' growing on sheep's wool mats (Figure 4a). Seemingly, this plant was only suitable for growing on sheep's wool vegetation mats to a limited extent. This might be due to its occasional drier requirements, which are better provided by coir mats or vegetation mats with a high proportion of coir [46].

Achnatherum calamagrostis 'Algäu' (Figure 4b) showed the best appearance on the coconut fibre mat. The sheep's wool mats seemed to be unsuitable, possibly due to the high nutrient content and high water capacity. Lower nutrient and drier sites are more suitable for this plant [46].

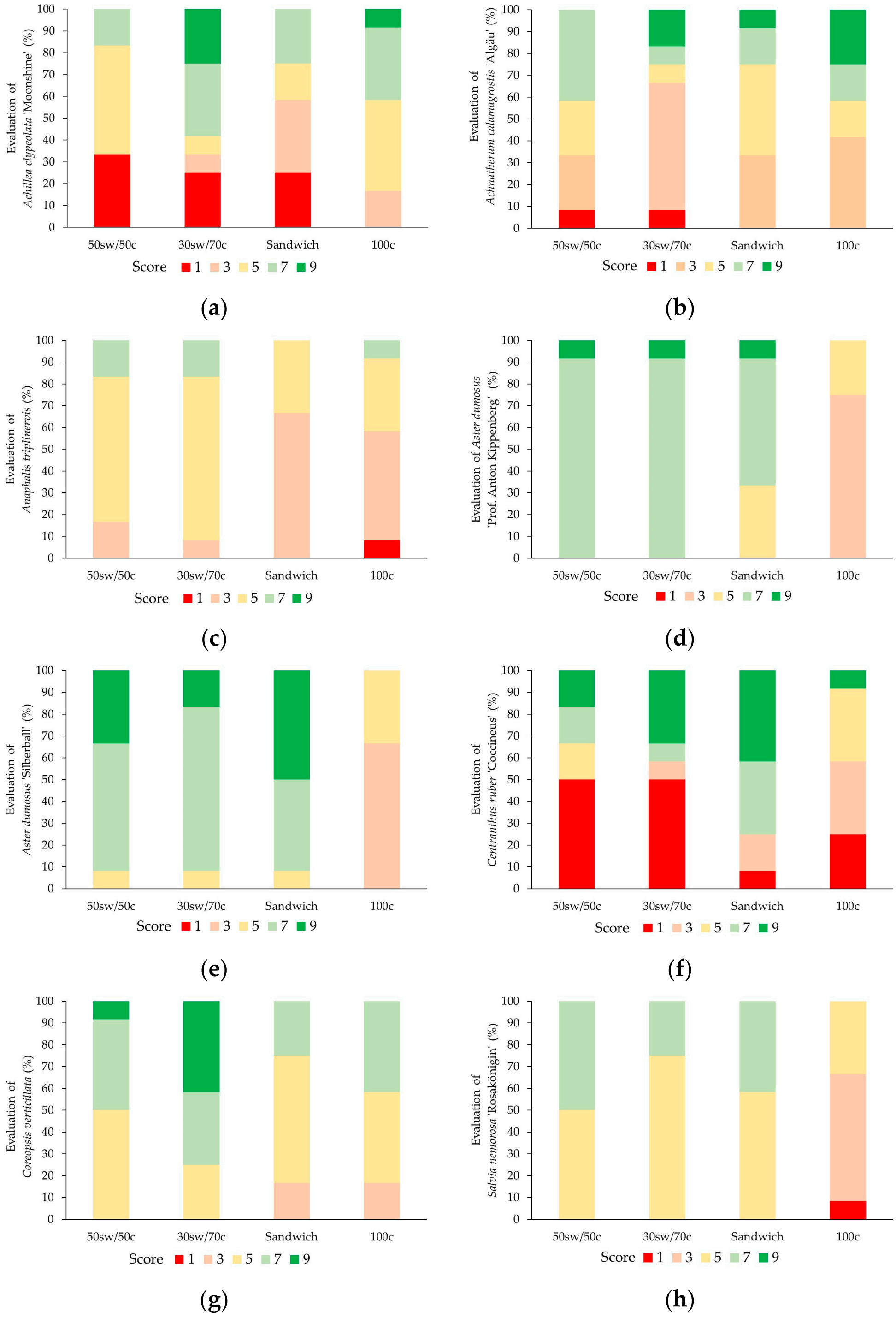


Figure 4. Influence of vegetation mats on overall impressions of individual perennials at the 7th assessment date (end of September 2015): 1 = plant failure, 3 = sufficient, 5 = satisfactory, 7 = good, 9 = very good for (**a**) *Achillea clypeolata* 'Moonshine', (**b**) *Achnatherum calamagrostis* 'Algäu', (**c**) *Anaphalis triplinervis*, (**d**) *Aster dumosus* 'Prof. Anton Kippenberg', (**e**) *Aster dumosus* 'Silberball', (**f**) *Centranthus ruber* 'Coccineus', (**g**) *Coreopsis verticillata*, and (**h**) *Salvia nemorosa* 'Rosakönigin'.

Anaphalis triplinervis (Figure 4c) showed the best overall performance on the 30sw/70c and 50sw/50c variants, although it tends to prefer dry soil [46]. Plant failures were observed only on the coir mat.

Aster dumosus 'Prof. Anton Kippenberg' (Figure 4d) tended to display the best appearance on vegetation mats 50sw/50c and 30sw/70c, even though the sandwich variant also seemed suitable. Perennials on the coir mat scored lower, on average, by at least two scores, possibly due to the lower nutrient content and lower water capacity of the mat. It should be emphasized that there was no plant failure on any of the vegetation mats.

Aster dumosus 'Silberball' (Figure 4e) showed the best overall impression on all vegetation mats with sheep's wool. Here, too, the perennials on the coir vegetation mat were, on average, at least 2 scores lower. There was no plant failure on any vegetation mat. Since asters have high nutrient requirements [46], they seem to be well-suited for cultivation on sheep's wool mats.

Centranthus ruber 'Coccineus' (Figure 4f) prefers rather dry and nutrient-poor soils [46]. Nevertheless, this perennial grew predominantly well to very well on the sandwich mat and much better than on the coir mat, where only 8% of the perennials were able to achieve a good overall impression. The highest number of plant failures were noted on the 50sw/50c and 30sw/70c, so this species seems unsuitable for these variants.

Coreopsis verticillata (Figure 4g) developed satisfactorily on all vegetation mats. There was no plant failure. This confirms the adaptability of the perennial [46]. The best overall impression was observed on variant 30sw/70c, which may be used for cultivating this perennial, prospectively.

Salvia nemorosa 'Rosakönigin' (Figure 4h) developed satisfactorily to well on all mats; once more, the good adaptability of the perennial to the different substrates was evident [46]. There was no plant failure.

According to the assessment scores, the results showed that perennial mats with sheep's wool were suitable for pre-cultivation—especially for *Aster dumosus* 'Prof. Anton Kippenberg' and *Aster dumosus* 'Silberball'—and, to a limited extent, for *Coreopsis verticillata* and *Salvia nemorosa* 'Rosakönigin'. *Achillea clypeolata* 'Moonshine' and *Coreopsis verticillata* were suitable for pre-cultivation on coconut mats; the other perennials, rather, were not.

3.4. Plant Height of the Individual Perennials

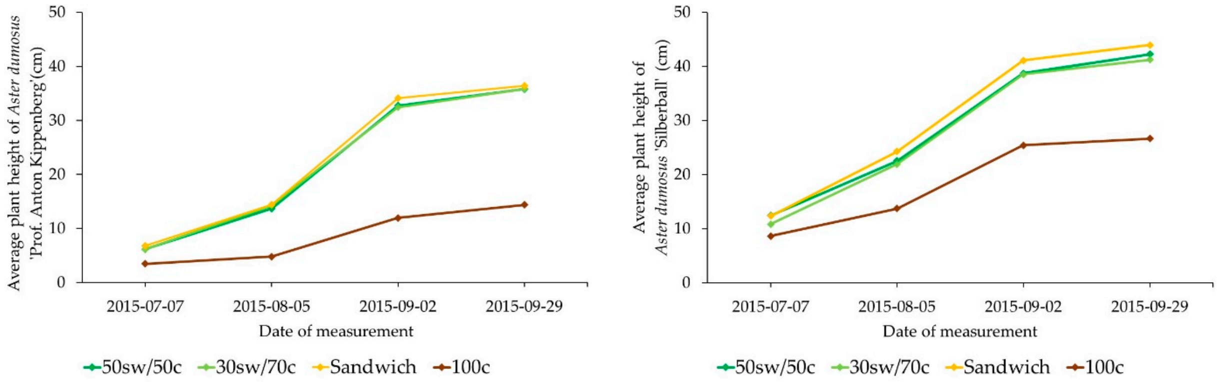
The positive development of the perennials can be seen not only in the awarding of a higher score but also in plant growth.

At the seventh assessment, the vertical growth of the eight perennials was good on all vegetation mats containing sheep's wool, partly even better than on the coir mat (Table 6). There were significant differences in plant height of *Achillea clypeolata* 'Moonshine', *Aster dumosus* 'Prof. Anton Kippenberg', *Aster dumosus* 'Silberball', and *Salvia nemorosa* 'Rosakönigin' cultivated on sheep's wool mats compared to coir mats. Plant growth was not significantly different on the three sheep's wool mat variants. In particular, the growth pattern of *Aster dumosus* 'Prof. Anton Kippenberg' (Figure 5a) and *Aster dumosus* 'Silberball' (Figure 5b) illustrate the advantage of sheep's wool mats compared to coir mats.

Table 6. Average plant height (± SE) of all perennials on different mat variants at the 7th assessment.

Mat Variants / Perennial	50sw/50c	30sw/70c	Sandwich	100c
	Plant Height (cm)			
Achillea clypeolata 'Moonshine'	25.3 ± 0.6 b	24.6 ± 1.2 b	25.1 ± 1.6 b	17.5 ± 1.3 a
Achnatherum calamagrostis 'Algäu'	46.5 ± 2.1 a	49.9 ± 1.5 a	45.7 ± 1.5 a	46.9 ± 1.2 a
Anaphalis triplinervis	28.8 ± 2.0 a	29.8 ± 1.6 a	25.6 ± 2.3 a	25.3 ± 1.3 a
Aster dumosus 'Prof. Anton Kippenberg'	35.8 ± 0.6 b	35.8 ± 0.8 b	36.5 ± 0.6 b	14.4 ± 1.8 a
Aster dumosus 'Silberball'	42.3 ± 1.1 b	41.3 ± 1.3 b	44.0 ± 0.9 b	26.7 ± 1.6 a
Centranthus ruber 'Coccineus'	51.0 ± 2.0 b	40.5 ± 5.8 ab	49.5 ± 2.2 ab	37.0 ± 3.8 a
Coreopsis verticillata	32.4 ± 1.4 a	29.2 ± 1.3 a	28.8 ± 2.2 a	29.0 ± 1.5 a
Salvia nemorosa 'Rosakönigin'	35.5 ± 1.9 b	37.5 ± 1.7 b	34.4 ± 2.7 b	22.2 ± 3.7 a

All values were tested with Tukey's HSD test. Different small letters indicate significant differences ($p < 0.05$).



(**a**) (**b**)

Figure 5. Effect of the different vegetation mats on the average plant height of (**a**) *Aster dumosus* 'Prof. Anton Kippenberg' and (**b**) *Aster dumosus* 'Silberball'.

The most significant correlations between the nitrogen content of the vegetation mat and plant height (Table 7), as well as between the water capacity at pF 1.0 and plant height (Table 8), could be observed for *Aster dumosus* 'Silberball' and *Aster dumosus* 'Prof. Anton Kippenberg" for all assessment dates. Significant correlations also occurred for *Salvia nemorosa* 'Rosakönigin' (1st–7th date) and *Achillea* 'Moonshine' (7th date).

Table 7. Pearson correlation between nitrogen content and plant height.

	1st Date	3rd Date	5th Date	7th Date
Achillea clypeolata 'Moonshine'	-	-	-	0.617 **
Sig. (2-tailed)	-	-	-	<0.001
Aster dumosus 'Prof. Anton Kippenberg'	0.542 **	0.808 **	0.878 **	0.834 **
Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001
Aster dumosus 'Silberball'	0.572 **	0.817 **	0.792 **	0.807 **
Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001
Centranthus ruber 'Coccineus'	-	-	0.372 **	-
Sig. (2-tailed)	-	-	0.009	-
Salvia nemorosa 'Rosakönigin'	0.437 **	0.536 **	0.561 **	0.446 **
Sig. (2-tailed)	0.002	<0.001	<0.001	<0.002

** The correlation is significant at a level of 0.01 (2-tailed).

Table 8. Pearson correlation between water capacity at pF 1.0 and plant height.

	1st Date	3rd Date	5th Date	7th Date
Achillea clypeolata 'Moonshine'	-	-	-	0.546 **
Sig. (2-tailed)	-	-	-	<0.001
Aster dumosus 'Prof. Anton Kippenberg'	0.494 **	0.699 **	0.770 **	0.722 **
Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001
Aster dumosus 'Silberball'	0.530 **	0.747 **	0.714 **	0.722 **
Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001
Salvia nemorosa 'Rosakönigin'	0.459 **	0.459 **	0.494 **	0.355 *
Sig. (2-tailed)	0.001	0.001	<0.001	0.014

** The correlation is significant at a level of 0.01 (2-tailed). * The correlation is significant at a level of 0.05 (2-tailed).

The data show (Tables 4–6) that mixed fleeces consisting of sheep's wool and coconut fibres should be used, in particular, for the pre-cultivation of perennials. Perennials with high nutrient requirements should be pre-cultivated on sheep's wool mats with at least 50% sheep's wool content.

The test results suggest that vegetation mats consisting of sheep's wool and coconut fibres lead to better height growth compared to conventional coconut fibre mats (Table 6, Figure 5). In the cultivation of perennials, the soil type and structure—in this case, the vegetation mat—is a contributing factor as well as the water and nutrient content [53]. Here, the use of sheep's wool is advantageous.

Although all vegetation mats received the same amount of irrigation and the same amount of liquid fertiliser during pre-cultivation, there was an additional positive fertiliser effect from the sheep's wool. *Aster dumosus* 'Prof. Anton Kippenberg' and *Aster dumosus* 'Silberball', especially, displayed strengthening and improved plant growth due to the sheep's wool and the associated higher water content (Figure 2, Table 4). However, the composition of the vegetation mats with sheep's wool or the amount of sheep's wool used was not significantly different for better plant growth (Table 5, Figure 3). Hence, it is necessary to choose the vegetation mat that is the most cost-effective for the manufacturing process, prospectively.

4. Conclusions

Further investigations should be carried out regarding the optimal amount of liquid fertiliser and irrigation during the pre-cultivation of sheep's wool mats, in order to be able to show a potential saving of fertiliser and water, if necessary. Not having to apply fertiliser weekly would also help reduce the required amount of labour, though the method of pre-cultivation (the planting of young plants on vegetation mats and regular irrigation) should remain.

Another question is whether thinner vegetation mats made of sheep's wool can also be used for the pre-cultivation of perennials to optimize the use of fibres and nitrogen input. In this way, different levels of nutrient requirements of perennials can be accommodated. It is important to determine which other perennial species are suitable for cultivation on sheep's wool mats.

In the future, the question of what advantages perennial mats with sheep's wool bring after installation in a target area should be investigated. The focus would be on the nutrient supply of the vegetation mats, as well as on the water capacity and water retention ability, in order to better buffer dry periods. A multi-year trial design is planned.

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