AHDB

Insulation materials for carrot field storage

Figure 1. Comparison of materials for in-field carrot storage

Key conclusions

- **Conventional straw treatments are inefficient in pure insulation terms**
- **Much of the frost protection provided by straw probably results not from its insulation value but from retention of water in the bottom layers of straw. This increases the thermal mass (reducing temperature fluctuations), reduces freezing due to latent heat, and results in evaporative cooling in the spring**
- **The main benefit of polythene below the straw is to increase the water content of the bottom layers of straw, to increase the effects noted above**
- **There is no evidence that light exclusion by polythene reduces regrowth or has any impact on crop quality**
- **Straw usage can be reduced by about two-thirds by putting polythene over the top instead of underneath**
- **All of the alternative treatments examined in these field trials provided effective insulation in both years of the trials (2015–16 and 2016–17), at all trial sites**
- **Cellulose-fibre insulation (a product derived from recycled paper) and similar material could be viable non-straw alternatives, with less potential for nitrogen lock-up and very clean crowns**
- **Closed-cell PE foam could easily be used as a supplemental layer with straw, if straw is in short supply**
- **Uncovered crops with exposed crowns and relatively little foliage are at greatest risk of frost damage**
- **For the shortest-term field storage (eg up to Christmas), cultivations to ensure crowns are covered with soil and/or covering with one or two layers of polythene may provide adequate protection**

Background

Winter storage of most UK carrot crops is done in situ in the field with a thick covering of wheat straw as insulation. Supplies of straw are becoming increasingly volatile and expensive, and bring with it concerns about the introduction of weed seeds. The application of large amounts of straw can also cause nitrogen lock-up for the following crop. This factsheet summarises the main findings of two recent AHDB projects (FV 398a, b) that examined the potential of alternatives to straw for field storage of carrots in the UK. The first project was concerned mainly with the theoretical aspects, whereas the second project examined different options in practice.

Aims

The overall aim of carrot field storage is to provide a continuity of supply of high-quality carrots during the period November to May. Carrots have a base temperature for growth of around 1°C, therefore the ideal storage temperature is in the range 0–2°C.

During the winter months, the main focus is on preventing the carrots (and soil) from freezing and, during the spring, the focus is on keeping the crop as cool as possible to prevent or minimise regrowth. Clearly, this also needs to be done while minimising costs and environmental impact.

Heat transfer principles and insulation

There are two physical principles of overriding importance: the first and second laws of thermodynamics. The first law states that energy can be transferred from one form/state to another but cannot be created or destroyed; the second law states that heat will flow from a hotter body to a colder body (Figure 2).

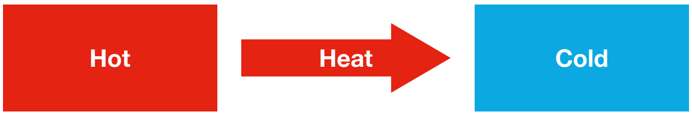

Figure 2. The second law of thermodynamics: heat will flow from a hotter body to a colder body

The temperature of the soil surface (and carrot roots) is dependent on the rate of heat loss or gain from the surface to the atmosphere and the rate of heat transport up and down the soil profile. The deeper layers of the ground/soil act as a reservoir of heat energy and, beyond a certain depth, (about 1m) the temperature of the soil remains almost constant.

Heat is gained or lost at the soil surface to/from the atmosphere by several different energy transport systems (conduction, radiation, convection and latent heat). The relative importance of each system varies with the weather conditions and time of day (Figure 3). Within the soil conduction is the most important means of heat transfer up and down the soil profile. Sand is a better conductor than peat, and wet soil is a better conductor than a dry soil, thus, on a cold night, there is less risk of the soil surface freezing for a wet sandy soil, than for a dry peaty soil.

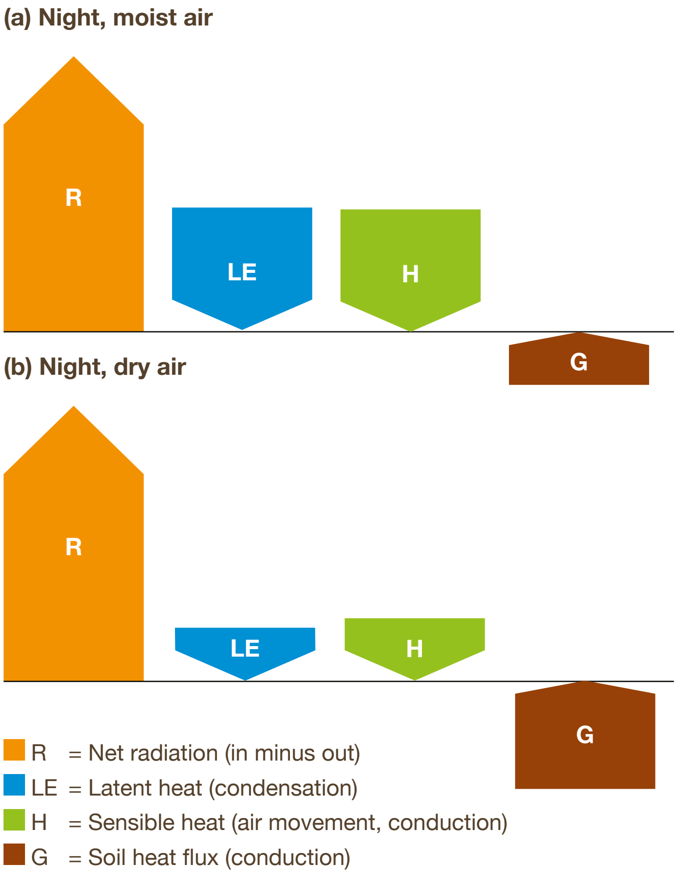

Figure 3. Soil surface energy balances at night under different conditions R + H + LE + G = 0

Frost penetration

When considering frost damage, we often conceptualise this as 'frost penetration', ie as the movement of 'cold' into the soil and down the soil profile, when actually it is the result of movement of heat upwards in the soil profile and heat loss from the soil surface. The surface layers cool when the rate of loss from the surface is greater than the rate of conduction of heat upwards. Effectively, the 'penetration' is the advance of the (below) zero-degree isotherm through the soil. The rate of advancement is slowed by the release of latent heat during freezing and, hence, is slower in soils with a higher water content, than in soils with a lower water content. The presence of ions and solutes in the soil water and in carrot tissues causes a depression in the freezing point, so the freezing front advances slightly behind the zero-degree isotherm.

Insulation

Adding a layer of straw (or other material) to the soil surface acts as an insulation layer, reducing heat loss during colder periods in the winter and reducing heat gain in the spring. In seeking alternatives to the current straw system, we first need to understand it.

The principles of heat transfer are well understood for soil/air systems and there is a lot of information on the theory of insulation from the fields of building and engineering. The insulation properties of materials are usually characterised using one or more of the following terms:

- k-value in W/mK is the intrinsic thermal conductivity of a material
- R-value in m^2K/W is the thermal resistance of a material, taking into account its thickness or depth
- U-value in W/m^2K is the thermal transmittance of a system, it combines the R values of all the components

Good insulators have low k- and U-values and high R-values, but note that a material with a relatively high k-value can give equivalent insulation to a material with a lower k-value by using a greater depth. The units used in these values are Watts (W) (= Joules per second), metres (m) or square metres (m^2), and Kelvins (K) (≡°C). Thus, a U-value of 1.0 means that 1 Watt is lost per square metre of surface area per degree temperature difference, so that if the temperature difference is 10 degrees, the rate of heat loss will be 10 times greater.

Table 1. Examples of insulation value (conductivity) values for some common materials

Material	k-value (W/mK)
Still air	0.024
Water (0°C)	0.563
Water (20°C)	0.596
Snow	0.05 to 0.25
Ice	~2
Sand (dry)	0.29
Sand (40% moisture)	2.2
Peat (dry)	0.06
Rockwool loft insulation	0.04
Straw bale (75kg/m^3)	0.052
Dry freshly laid straw (12kg/m^3)	0.1

Low k-value = good insulator

Still air is an excellent insulator. Many insulation materials, especially those used in buildings (ie loft and wall insulation, double-glazing), work by trapping pockets of still air, but for this to work efficiently:

- Air pockets must be small to prevent convection (this is why the air gap in double-glazing should not be too large)
- There must be no continuous air gaps (this is why draft proofing is important)

Current straw system

Characterising the current straw system is problematic: it is dynamic and thermally unstable. It is very inefficient in pure insulations terms, but nevertheless it works.

The insulation (k-values) of straw are very variable:

- Straw is typically laid to produce a light fluffy layer. At typical densities (about 12kg/m^3 when first laid), there is a continuum of air space from top to bottom and air pockets are relatively large
- The surface is open, so heat loss is affected by air/wind penetration into the surface layers
- The straw becomes moist/wet, this increases conduction and increases the role of latent heat

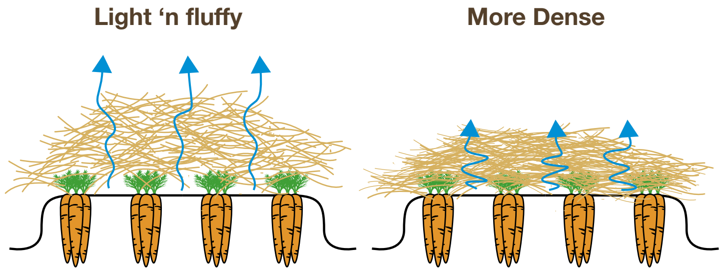

Figure 4. The effect of density on air movement (convection) through straw

Thermal bridging is another factor that reduces the overall insulation value of a system. Typically, most of the straw is applied onto the beds, with less straw in the wheelings. The wheelings then act as thermal bridges, increasing the overall heat loss in a field:

- Heat moves horizontally as well as vertically
- Heat follows the path of least resistance
- Wheelings comprise approx. 16 per cent of field area – significant heat loss from thermal bridging
- Straw filling in the wheelings is a good thing

Theoretical insulation value of alternatives

In project FV 398a, the theoretical insulation values of a range of different alternatives to the current system were calculated, and these were used as the basis for selecting the systems to be examined in trials conducted in project FV 398b.

The comparisons were made on the basis of theoretical U-values for the system as a whole (low U = good insulator) and with the ideal requirements of:

- Equivalent/better insulation than current straw systems
- No more expensive than current system
- Biodegradable or reusable
- Similar or lower transport costs (lower bulk)
- Laid as quickly, with similar labour to current system

Both reduced straw and non-straw alternatives were examined, and examples are show in Tables 2 and 3.

Table 2. Comparison of U-values for conventional and reduced straw alternatives. The moisture content and straw depth represent the measured straw moisture content in a typical strawed crop

System	Bales per ha	Depth (cm)	Moisture (%)	U-value (W/m^{2}K)	Material cost (£/m^2)
Dry straw	90	15.5	0	1.42	0.31
Dry straw over poly	90	15.5	0	1.17	0.36
Moist straw	90	15.5	286	1.97	0.31
Moist straw over poly	90	15.5	286	1.52	0.36
Poly over dry straw	29	5	0	1.09	0.15

Low U-value is better

Reduced straw

The current straw system is inherently inefficient as an insulator, due to moisture and the open surface. Adding the polythene layer below increases the theoretical overall insulation value (reduces U-value) by trapping air, and is equivalent to about 5cm depth of straw.

Calculations suggest that making more efficient use of straw by keeping it dry, and eliminating forced convection, would have a major impact on the amount of straw required. This could be achieved by covering the top of the straw layer with a layer of polythene. Results indicate that a 5cm layer of dry straw covered with polythene would provide the equivalent insulation to 28cm of uncovered, wet straw, or 20cm of uncovered, dry straw. Thus, potential savings in the amount of straw needed of up to 75 per cent could be achieved simply by covering the straw with a layer of polythene.

Non-straw alternatives

In principle, any material covering the soil surface will reduce heat loss and the risk of frost damage. A wide range of alternative insulation materials have the potential to achieve equivalent or better insulation values to straw, especially if they can be kept dry; examples are shown in Table 3.

Plant-based, straw or straw-like materials are likely to have similar intrinsic insulative properties to straw if they can be applied at sufficient depth and at sufficient bulk density. But they would also have the same issues with moisture and forced convection, and N lock-up for subsequent crops. Nevertheless, if alternative fibrous materials can be obtained locally at low cost, they may be worth investigating as to the amounts needed to achieve sufficient depth and density to replace straw.

At present, most of the non-straw alternatives are likely to be more expensive than straw, so only become feasible if they can be reused several times or if the price of straw further increases. On the other hand, costs of some materials could come down if purchased in the bulk quantities that would be required for carrot field storage.

The cheapest non-straw alternative considered was a layer of PAS100 composted green waste sandwiched between polythene. However, it was rejected, as the amount required (up 200t/ha) would preclude its use due to nitrogen application limits. Bark or wood shavings sandwiched between polythene are also among the cheapest alternatives, but the amount required to achieve adequate depth (80 to 100t/ha) would have much greater impact on N lock-up than straw. Possibly the two effects could be combined, eg a mix of green waste and wood shavings would counteract each other and effectively provide long-term slow release of N into the soil. However, the dynamics of N release and availability in such a system would need further study to ensure there were no detrimental cropping and environmental impacts.

Although relatively expensive initially, closed-cell PE (polyethylene) foam, was considered worthy of further consideration. This is the material typically used in outdoor sleeping mats and as frost protection for freshly laid concrete. It has the major advantage that, unlike most other materials (including straw), its insulation value is unaffected by moisture. It is robust and would have the potential to be reused for several years, and would not require covered storage. We could envisage this could be

Table 3. Calculated U-values and material costs for selected alternative field storage options

System	t/ha	Density (kg/m^3)	Depth (cm)	kg/m^2	k-value (W/mK)	U-value (W/m^2)	£/m^2	Notes
Moist straw (90 bales/ha)	45	28.6	15.5	4.43	0.31	1.97	0.31	Current system
SF19 (multifoil) building insulation	6.9	-	3.8	0.69	-	0.42	5.00	Exceeds insulation needs
TLX Gold (breathable) roof insulation	9	-	3.3	0.90	-	0.91	1.50	Price indication from manufacturer
Poly + Rockwool + poly	5	10	5	0.50	0.044	0.70	2.00	Only effective if dry
Poly + 2 layers Vattex[1] + poly	7.5	94	0.8	0.75	0.037	1.96	2.40	
Poly + 1 layer Vattex + poly	3.8	94	0.4	0.38	0.037	2.49	1.20	
Closed cell PE foam	2.6	35	0.75	0.26	0.037	2.89	1.46	Most easily reused, with longest life
Closed cell PE foam	7.0	35	2	0.70	0.037	1.46	3.68	
Poly + cellulose fibre + poly	17.5	35	5	1.75	0.044	0.70	0.80	Cheapest realistic alternative
Poly + PAS100 GW + poly	200	400	5	20.0	0.060	1.02	0.07	Would exceed N limits
Poly + starch peanuts + poly	3.25	6.5	5	0.325	0.040	0.65	1.72	Difficult to handle, only effective if dry
Poly + wood shavings + poly	80	160	5	8.0	0.065	0.94	0.72	Issues with N-lock up
Poly + bark	107	213	5	10.7	0.060	0.89	1.10	Issues with N-lock up
Foil/bubble wrap			0.4		n/a	3.75	1.49	
Poly alone		0	0		n/a	6.67	0.05	

Low U-value is better

[1] Capillary matting

most readily used in the short-term as a replacement for the polythene layer under a reduced straw layer for later crops. Key factors affecting its feasibility would be the number of times it can be reused, the availability of a suitable storage area, and the cost of final recycling for disposal.

Cellulose fibre in a polythene sandwich (to keep it dry) was another alternative that could become feasible as a single-use option if straw costs increase. This is an industrial 100 per cent recycled cellulose-fibre-type product, similar to those used in building insulation (but without the fire retardants) and with similar insulation properties.

Although the previous theoretical comparisons of different options were on the basis of insulation values, it became clear during the first year of trials that retention of water and, so, thermal mass and latent heat effects may have a significant impact on the value of different materials (see comments on the various treatments in the following section).

Field trials

Field trials were done over two years (2015–16, 2015–17) and at three sites (Aberdeenshire, Norfolk and Yorkshire) to evaluate and refine different treatments. Data loggers were used to monitor soil temperatures at different depths on an hourly basis in order to calculate heat loss/gain and estimate the insulation value of different systems. Although, in theory, the insulation value should be the same for heat transfer into and out of the soil surface, apparent U-values were calculated separately for heat loss (U-out, when soil temperature is greater than air temperature, and for heat gain (U-in, when air temperature is greater than soil temperature). This enables separate comparison of the relative merits of system for shorter-term storage (when reducing heat loss to prevent frost damage is most important) and longer term (when, as well as preventing heat loss, we want to minimise heat gain to prevent regrowth). The relative merits of each of the systems are discussed in the following sections.

Table 4. Relative U-values (W/m^{2}K) for heat loss (U-out) and heat gain (U-in) for the different insulation materials examined in 2016–17 field trials

Treatment	U-out	U-in
Uncovered	15.2	10.9
Straw only	3.2	3.7
Straw over poly	2.2	2.0
Poly over reduced straw	3.3	3.2
Closed cell PE foam	4.9	5.3
Cellulose fibre	2.5	3.4
Poly over fibre	4.6	3.0

Low U-value is better

Uncovered

Figure 5. Uncovered control

This treatment was included as a negative control. Inevitably, the harvested carrots had significant levels of frost damage, and reduced marketable yields compared to the covered plots.

It would be expected that levels of frost damage would be correlated with how cold each site was, and this was the case in 2015–16 where the most severe damage occurred at the coldest site (Aberdeenshire). In 2016–17, this was not the case; the coldest site was again Aberdeenshire, but there was no frost damage at the first harvest (end of January) and damage was still at a relatively low level at the second harvest, with the most severe frost damage seen at the Yorkshire site. The most likely reason for the difference was that at the Scottish site, the crowns were not exposed and were generally at or below the soil line, whereas, at the Yorkshire site, crowns were exposed and often 1cm above the soil line. There was also a greater mass of foliage at the Scottish site, which could in itself reduce the rate of heat loss from the soil surface. This suggests that simply ensuring crowns are covered with soil (eg by choice of variety or by cultivating between rows to ensure they are covered) could eliminate the need for, or reduce, the amount of straw required for earlier harvested crops.

Straw only

Figure 6. Conventional straw only

Growers tend to use straw alone for shorter-term crops, or when the crop may be processed and some damage to crowns is acceptable. This treatment provided less insulation than straw over poly. The straw remains wet at the bottom (but not as wet as straw over poly), and based on moisture contents at the final harvest, the water content was equivalent to up to 8kg/m^2. This has several effects: providing a thermal mass effect (dampening of temperature fluctuations), latent heat effects (the water in the straw will freeze before the soil/crop) and evaporative cooling. It is likely that both the thermal mass effect and the protection resulting from release of latent heat when water in this layer freezes is an important aspect of the protection provided.

Straw over poly

Figure 7. Conventional straw over poly. Straw at 1/3rd rate with poly cover to keep drier and maximise insulation

Growers planning long-term field storage of crops generally use straw over poly. The introduction of a polythene layer provides additional insulation through surface resistance to heat transfer and, so, provides slightly greater insulation than straw alone. However, the most important effect of the polythene was that the straw remains much wetter than straw alone (up to twice the moisture content), and often with free water on the surface of the polythene. Based on moisture contents of the straw at the final harvests, the water content was equivalent to as much as 14kg/m^2. This larger amount of water provides a greater thermal mass, greater potential latent heat effects and evaporative cooling. Thus, not only is the crop more protected from freezing, but it also heats up more slowly in the spring (ie is kept within a narrower temperature range than the other treatments).

It has been suggested that the benefit of the polythene under straw was light exclusion and this prevents regrowth. There is no evidence for this. The beneficial effect of the polythene perceived by growers is primarily a result of the greater thermal mass, and evaporative cooling effects, which in turn maintain soil and carrots at a lower temperature in the spring.

Poly over reduced straw

Figure 8. Poly over reduced straw

This was a modification of a reduced-straw polythene sandwich treatment examined in the first year of trials; simplified by omission of the polythene layer below the straw and using a minimal amount of straw in the wheelings to anchor the polythene.

The omission of the lower layer of polythene made little difference to the overall insulation values, while reducing costs and making it more practical for field scale deployment. Whereas in the first year the top layer of polythene was anchored using staples and bags of soil, in the second year the polythene was anchored by dropping a relatively small amount of straw in the wheelings (1kg per m). This proved largely successful; on the few beds and occasions when the straw became partially exposed only, this tended to occur from the anchor points at the ends of the plots (held by bags of soil) rather than the sides (which would not be an issue on a field scale) or towards the end of the trial in the spring when the straw dried out at one of the sites.

This treatment could feasibly be implemented by using a wider polythene sheet (2.5m) and with modifications to existing straw laying machinery: setting up so the polythene unrolls over the top of a reduced quantity of straw and redirecting a small proportion of the straw on top of the polythene to provide anchorage.

Closed-cell PE foam

Figure 9. Closed-cell polyethylene foam. Used for camping mats, insulation value is unaffected by moisture

This treatment consisted of a 1.8m wide, 7.5mm thick layer natural/white closed-cell polyethylene foam laid directly over the crop and secured with a wider layer of white polythene over the top. The material is relatively expensive and would only be cost-effective if reused. It is available in different thickness, but thicker versions increase cost. We therefore examined the thinnest version with a view to using it on its own for earlier harvests or as an adjunct to other materials. The great advantage of this material is that the closed-cell nature (ie air is trapped in closed cells) means its insulation properties are unaffected by moisture, unlike, eg rockwool insulation and similar materials used in buildings. Based on the theoretical predictions, it was expected that this treatment would have the lowest insulation value, and this proved to be the case. Nevertheless, it still provided adequate protection at all sites in both years, and we were able to recover it intact for reuse at the end of each year.

One aspect of this treatment not anticipated was that both it and the polythene cover were translucent, this meant that, unlike with all the other treatments, the crop foliage remained green throughout, although this did not have any noticeable/measurable direct effect on crop quality either way. The more translucent nature may also have contributed to a 'greenhouse' effect contributing to the relative greater increase in incoming U-value compared to the other treatments.

Fibre only

Figure 10. Cellulose fibre. Used for house insulation, made from waste paper. Absorbs a lot of water

This treatment was envisaged as the simplest way to make use of the cellulose fibre on a commercial field scale. The product was blown onto the crop using a petrol leaf blower with a flexible outlet. The rate used (1.75kg/m^2) was the same as used in the other fibre treatments, and intended to give a 5cm depth of material. There was concern that the material would not stay in place on the crop without a cover but this proved to be unfounded. The carrot foliage trapped the initial fibres, and there was very little drift off the target bed. In addition, once the surface had been wetted by the first rain or dew following the initial application, the top layer of material formed a crust, and stayed locked in place for the duration of the winter until harvest.

In terms of frost protection, the material was equivalent to the straw treatments with comparable U-values. Most of the winter, the product remained quite wet and, when temperatures were coldest, a frozen layer developed in the top 1–2cm. The material is not quite so effective at preventing warm-up in the spring compared to straw over poly. This is probably because the overall mass was lower and, therefore, the maximum water content was also lower. Measurements in the first year indicated that the fibre can absorb up to 600 per cent of dry weight in water when saturated, but at harvest was down to 27 to 75 per cent depending on site.

It was notable that the crowns of the roots from under the fibre had a better visual appearance than roots from the other treatments (Figure 11). We suspect this may be due to its relative water absorbency, and freedom from microorganisms.

Figure 11. Cellulose fibre results in noticeably cleaner crowns

From a practical perspective, this treatment is the most feasible non-straw alternative, providing equivalent frost protection to conventional straw, but requiring less mass, and so less potential for nitrogen lock-up, better visual quality of the roots, and with no risk of weed or disease introduction. It is likely that there could be several options for field application, depending on the form of delivery and ease of adaptation of machinery. Different application methods would likely result in subtle differences in the structure of the layer, therefore additional trials would be appropriate to look at the influence of different application methods on performance.

Testing indicates that there are no concerns about heavy metals (undetectable) or other contaminants and similar materials have been marketed as mulches and soil improvers. Similar fibrous materials and other forms of waste paper products may be available locally, and at a lower price, eg unprocessed shredded paper, wet pulp, paper crumb, these could also be realistic alternatives but their ability to stay in place, the mass/volumes required, etc. would need to be established. There may also be a need to check with the Environment Agency whether a permit is required.

Poly over fibre

Figure 12. Poly over fibre. Aiming to keep the fibre drier and maximise insulation

This treatment was examined in the second year and was essentially a modification of the poly-fibre sandwich from the first year, modified by removal of the bottom layer of polythene, as it was found that due to the smooth surface of the polythene, the fibre tended to fall off the shoulders of the beds, resulting in an variable depth or absence of insulation material in places. Removing the bottom layer resulted in improved and even coverage. The polythene over the top was intended to keep the material in place, ie preventing it from blowing away and keep the material drier than in the fibre-only treatment, and this was indeed the case.

In terms of frost protection, the material had a slightly higher outgoing U-value than the field-straw systems. This is probably a result of the lower moisture content providing less thermal mass and protection via latent heat. The material is not quite as effective at preventing warm-up in the spring compared with the field standard, with similar incoming U-values to the fibre-only and poly-over-reduced-straw.

Given that this treatment did not provide any insulation benefit compared with the fibre-only, and that the fibre-only stayed in place without a cover, there would be no justification for the additional cost and extra complication of covering the fibre with a layer of polythene.

Notes

All costs/prices should be considered as relative values that were estimated at the time of original publications from which they were extracted.

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Photographic credits

Further reading

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