Durability and Agronomic Performance of New Paper-Polylactic Acid (PLA) Composite Weed Barriers in Nebraska and Costa Rica

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ABSTRACT. **Mulch weed barriers are an important crop management tool on certified organic and naturally grown specialty crop farms. However, narrowly spaced, high-density crops are not compatible with mulch weed barriers because the number of holes required for planting compromises mulch function. Biobased, compostable weed barriers (BCWBs) have been developed for these crops whereby seeds can be planted on top of the mulch with compost and root through it, but the mulch still suppresses weeds below it. Newly commercialized composite, paper–polylactic acid (PLA) BCWBs were developed for this purpose, but their durability and agronomic performance have yet to be tested. The objective of this study was to evaluate the durability of paper–PLA composite BCWBs and their effects on soil and crop growth in contrasting field environments of Nebraska, USA, and Guanacaste, Costa Rica. Three experiments were conducted to evaluate 1) effects of a two-layer paper–PLA BCWB on weed emergence and lettuce yield in Nebraska using two planting approaches (broadcast across the entire barrier vs. planting in two wider furrows), 2) the durability and deterioration of two- and three-layer paper–PLA BCWBs and their effects on soil moisture and temperature in Costa Rica, and 3) effects of two- and three-layer paper–PLA composite BCWBs on growth and yield of lettuce and onion transplanted through the mulch. In Nebraska, the two-layer PLA–paper BCWB reduced weed emergence by 91% to 95% in lettuce, regardless of planting approach. There was no difference in lettuce yield between BCWBs and hand-weeded bare soil, although seedling establishment was greater in compost on the BCWBs compared with bare soil. The loose texture and porosity of compost compared with bare soil may reduce mechanical resistance for emerging seedlings (i.e., soil crusting). However, in Costa Rica, compost seed furrows were drier and warmer compared with bare soil (2.5 cm depth), which illustrates the trade-offs of planting into compost on BCWBs. Deterioration of paper in the two-layer BCWB reached 12% by 64 days after application in Costa Rica, but paper in the three-layer BCWB showed no signs of deterioration. Lettuce growth and onion yield in Costa Rica were not different between two- and three-layer BCWBs, suggesting the durability and weed suppression provided by the two-layer BCWB may be adequate for annual crops. Future research is needed to explore the potential for the three-layer BCWB to provide longer-term weed suppression in perennial crops and landscape plantings.**

Mulching is an important management practice for specialty crops that, depending on mulch properties, can modulate soil temperatures, conserve soil moisture, suppress weeds, and increase yield (Tofanelli and Wortman 2020). Polyethylene plastic mulch film is the most commonly used mulch in production horticultural systems in part because of its capacity to increase soil temperatures, control weeds, and increase crop earliness and yield at a relatively low cost. However, plastic mulch films must be removed from the field after use and are then commonly transported to a landfill or burned, potentially degrading soil and air quality (Madrid et al. 2022). Even after field removal, some small fragments of plastic mulch inevitably remain in the field and can persist in soil for hundreds of years (Ohtake et al. 1998). These residues may accumulate and deteriorate into micro- or nanoplastics that can degrade soil quality, adhere to roots or modified stems, or accumulate in growing plants (Azeem et al. 2021; Madrid et al. 2022).

Another important limitation of plastic mulch film is that it is not compatible for use with narrowly spaced, high-density plantings of crops such as leafy greens, onion (*Allium cepa*), carrot (*Daucus carota*), pea (*Pisum sativum*), beet (*Beta vulgaris*), or matted row strawberry (*Fragaria* ×*ananassa*). For these narrowly spaced crops, the number of holes that would be required in the mulch to plant or propagate would compromise its function. As a result, weed control is especially difficult in narrowly spaced specialty crops, particularly in US Department of Agriculture Certified Organic or Certified Naturally Grown fields where synthetic herbicides are prohibited. In the absence of mulch or herbicide options, many growers resort to hand-weeding, which is labor-intensive and expensive (Tiwari et al. 2022).

Biobased, compostable weed barriers (BCWBs) made from nonwoven polylactic acid (PLA) fabric have been demonstrated as an alternative, nonchemical weed management solution for narrowly spaced, high-density crops including lettuce (*Lactuca sativa*) and carrot (Tofanelli et al. 2021; Wehrbein et al. 2024). Tofanelli et al. (2021) first demonstrated the capacity for crops to be seeded on and grow through PLA-based BCWBs without negative effects on lettuce or carrot yield under greenhouse conditions. Wehrbein et al. (2024) found that growing carrot on and through similar PLA-based BCWBs in the field reduced weed emergence by 90% to 96% without adverse effects on carrot growth or yield.

The BCWBs tested by Wehrbein et al. (2024) were two-layer composites that included a white spunbond PLA layer (30 $g \cdot m^{-2}$) and a black meltblown PLA layer (ranging from 50 to 90 $g \cdot m^{-2}$). Although these formulations were effective, commercialization potential was limited by the cost of PLA resin, which was highest in the black meltblown layer. The primary function of the black meltblown layer is to filter and exclude light whereas the white spunbond layer has greater tensile strength and physical barrier properties (Korkmaz et al. 2023). Therefore, it may be possible to replace the black meltblown layer with a lower cost biobased material that provides similar functions. Nonbleached, kraft paper, a more durable paper due to lower lignin content, is a possible alternative to the meltblown PLA layer because it is less expensive, biobased and compostable, porous (to water, air, and potentially plant roots), reduces light transmission to the soil, and already a commonly used weed barrier material (Brault et al. 2002; Haapala et al. 2014). Moreover, because paper is hydrophyllic [compared with nonwoven PLA, which is typically hydrophobic (Sundar et al. 2020)], it may serve to retain moisture near seeds germinating on the BCWBs and improve seedling establishment (Shankar and Rhim 2018).

Combining a spunbond PLA layer and a paper layer into a composite BCWB may address the limitations of each when used alone as weed barriers. Spunbond nonwoven PLA has high physical strength and is stable in soil throughout the growing season but is transparent and weeds can grow beneath it (Wortman et al. 2016). Paper mulch effectively filters most light to prevent weed growth beneath it (Brault et al. 2002) but is easily biodegraded in soil, particularly where the mulch edges are buried, and can be lost to high winds early in the season (Moreno et al. 2017). Combining paper and PLA layers into a composite BCWB may result in a more durable and functional weed barrier with properties well suited for growing narrowly spaced, high-density crops on and through it, and for use as a traditional weed barrier (i.e., seedling planted into punched holes). The objective of this study was to evaluate the durability of paper–PLA composite BCWBs and their effects on soil and crop growth in contrasting field environments of Nebraska, USA, and Guanacaste, Costa Rica.

Materials and methods

To accomplish the objective of this study, we initiated three field experiments. The first experiment was conducted in Lincoln, NE, USA, and designed to evaluate the effects of a paper–PLA composite BCWB and two planting methods on weed density and loose-leaf lettuce yield. The other two experiments were conducted in Santa Cruz, Guanacaste, Costa Rica. The first was designed to evaluate the durability and deterioration of two- and three-layer paper–PLA BCWBs and their effects on soil moisture and temperature, and the second was designed to evaluate the effects of a two- and three-layer paper–PLA BCWBs on lettuce growth and onion yield.

Expt. 1: Mulch performance in lettuce in Nebraska. Expt. 1 was conducted at the University of Nebraska–Lincoln East Campus Research Farm (Lincoln, NE, USA; lat. 40°50′12″N, long. 96°39′48″W) in 2023 between August and September. Soil type was a Zook silty clay loam (soil organic matter = 5.2%; pH = 7.0). Pigweed (*Amaranthus* sp.) and large crabgrass (*Digitaria sanguinalis*) were the dominant annual weeds in the field. The experimental design was a randomized complete block with four replicate blocks and three treatments. Treatments included the following: 1) a two-layer paper–PLA composite BCWB (Root-Thru Weed Barrier; Sage Eco-Innovations, LLC, Lincoln, NE, USA) with lettuce drop seeded on the mulch to mimic the outcomes of hand-broadcast seeding ("mulch broadcast"); 2) the same BCWB with lettuce direct seeded into two parallel seed furrows on the mulch ("mulch furrow"); and 3) a bare soil, no mulch control with lettuce seed direct seeded into two parallel seed furrows in the soil ["bare soil furrow (control) treatment"] (Fig. 1). The BCWB PLA layer was white with a 30 $g \cdot m^{-2}$ mass basis and the paper layer was brown with a 75 $g \cdot m^{-2}$ mass basis (105 $g \cdot m^{-2}$ total mass basis; 0.4-mm thickness). Each replicate treatment plot was 1.2 m wide (raised bed width) by 4.3 m long with 3.1 m between the center of each bed.

The field was prepared by rototilling to remove weeds and improve soil tilth. Soybean meal organic fertilizer was broadcast applied at a rate of 85 $kg \cdot ha^{-1}$ N and mixed into the soil when raised beds were shaped with a bed shaper (RB-448; Nolt's Produce Supplies, Leola, PA, USA). In the mulch broadcast treatment, the BCWB (1.22 m width) was applied by hand over flat-bed tops. The PLA layer of the composite was facing up, and the paper layer was facing the soil. A thin layer of compost (∼1 cm deep; municipal yard waste feedstock) was drop spread (BCS Spreader; BCS America, Oregon City, OR, USA) over the mulched bed top and lettuce seeds ('Encore'; Johnny's Selected Seeds, Waterville, ME, USA) were drop seeded (Jang JP-3 Three-Row Push Seeder; Jang Automation Co., Seoul, South Korea) in six rows spaced 10 cm apart into the compost on top of the BCWB at a rate of ∼468 seeds per linear bed m (78 seeds per row by six rows spaced 10 cm apart across the bed top). A second layer of compost (∼1 cm deep) was broadcast spread over the planted seeds. Two lines of drip irrigation tape (0.55 gal/min/100 ft of drip tape; Irritec, Fresno, CA, USA) were laid on top of the planted beds; beds were irrigated for 90 min daily to ensure germination, seedling establishment, and rooting through the BCWB.

In the mulch furrow treatment, two seed furrows or ridges (5 cm deep and 7.5 cm wide at the top) spaced 30 cm apart were created on the bed top with a row maker (Hoss Row Maker; Hoss, Norman Park, GA, USA) and then the BCWB was applied by hand over the bed top and pressed into the furrows. The PLA layer of the composite was facing up and the paper layer was facing the soil. Compost was drop spread onto the bed tops to an approximate depth of 1 cm and consolidated into the prepared furrows with a broom. Lettuce was direct seeded into the furrows to a depth of ∼1 cm at a rate of 270 seeds per linear bed m (135 seeds per row by two rows spaced 30 cm apart centered on the bed top).

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Fig. 1. Lettuce growing on and through the two-layer, paper–polylactic acid, biobased, compostable weed barrier in the mulch broadcast (left) and mulch furrow (middle) treatments, and in the bare soil furrow (control) treatment (right) 36 d after planting in Lincoln, NE, USA.

Two lines of drip irrigation tape were laid on top of the BCWB adjacent to the furrows, and beds were irrigated daily consistent with the mulch broadcast treatment.

In the bare soil furrow (control) treatment, lettuce seeds were direct seeded into soil on prepared bed tops in two rows spaced 30 cm apart to a depth of ∼1 cm at a rate of 270 seeds per linear bed m (135 seeds per row by two rows spaced 30 cm apart centered on the bed top). No compost was applied to beds or seed furrows in the control treatment, which allowed for comparison of the BCWB mulching system (mulch plus compost required for seedling establishment) and a conventional system with no mulch or compost intervention. Mechanistic effects of compost and mulch in this BCWB system were evaluated by Wehrbein et al. (2024), but a "no-mulch plus compost" control treatment was not included in this systems evaluation. Irrigation setup and rates were identical to the mulch treatments.

Data collection in Expt. 1 included weed density, lettuce stand density, and fresh yield. Emerged weeds were counted within two randomly located quadrats (0.3 × 0.3 m) centered on the bed top of each plot at 9, 21, and 29 d after planting and summed to determine season-long weed emergence. After counting weeds, all weeds in the plot (inside and outside the quadrats) were removed by hand. Lettuce stand density was counted throughout the plot 9 d after planting. Lettuce was harvested 34 and 49 d after planting with a handheld leafy greens harvester (Quick Cut Greens Harvester; Farmers Friend, Centerville, TN, USA) by cutting 5 cm above the soil or mulch surface. Harvested lettuce from each plot was weighed fresh to determine yield.

Expt. 2: Microclimate and mulch deterioration in Costa Rica. Expt. 2 was conducted at the University of Costa Rica Santa Cruz campus (Santa Cruz, Costa Rica; lat. 10°17′8″N, long. 85°35′30″W) in 2023 between October and December. Soil type in the field was classified according with Soil Survey Staff (2014) within the soil order Alfisols (soil organic matter = 4.23%; pH = 5.9; sand = 28%; silt = 37%; clay = 35%). Chamber bitter (*Phyllanthus urinaria*) and purple nutsedge (*Cyperus rotundus*) were the dominant weeds in the field. The field was prepared by rototilling to remove weeds and improve soil tilth.

Treatments included a two-layer paper–PLA composite BCWB (RootThru Weed Barrier); a three-layer PLA–paper–PLA composite BCWB (RootThru Max Weed Barrier) and a bare soil control. The two-layer BCWB was identical to the BCWB used in Expt. 1. The three-layer BCWB included white, nonwoven PLA (30 $g \cdot m^{-2}$ mass basis) in the top and bottom layers and a brown paper inner layer with 150 $g \cdot m^{-2}$ mass basis (210 $g \cdot m^{-2}$ total mass basis; 0.8-mm thickness).

Plots (1.22 m wide by 5.0 m long) were established on 10 Oct 2023 using the furrow methods described in Expt. 1. Furrows on the BCWBs were filled with a locally available compost (BIOECO Biofertilizer; BIOECO, San Carlos, Alajuela, Costa Rica) to a depth of 5 cm. Two lines of drip irrigation tape were laid on top of the BCWB (or soil in control plots) and adjacent to the seed furrows, and beds were irrigated daily beginning on 20 Oct Cilantro ('Slo-Bolt') was seeded into the furrows on 10 Oct but did not emerge due to intense seed predation by birds among all plots.

In the absence of crop growth, these plots were used to evaluate deterioration of the BCWBs over time in the humid tropical climate of Costa Rica. The PLA layer of the BCWBs remained stable throughout the experiment, but deterioration of the paper layer (visible beneath the top PLA layer) was quantified through image analysis at 33, 48, and 64 d after mulch installation. Photos of each plot were taken 1 m above the canopy and the area of degraded paper was compared with the total BCWB area in the image to determine percent degradation (ImageJ; Ferreira and Rasband 2012). Paper was considered degraded when soil was visible through the remaining PLA layer(s) of the BCWB.

Microclimate data were collected from two nonreplicated plots that included a three-layer BCWB and a bare soil control treatment. A solar-powered microclimate weather station assembled between plots and equipped with cabled sensors for measuring and logging (CR1000; Campbell Scientific, Inc., Logan, UT, USA) precipitation, air temperature, and soil temperature (Thermocouples; Omega Engineering Inc., Norwalk, CT, USA) as well as soil water content (Sensor Teros 10; Meter Group Inc., Pullman, WA, USA) in the seed furrow (2.5-cm depth) and beneath the BCWB and soil (5- and 15-cm depths). Data were logged every 30 min between 12 Oct and 13 Dec. Data were used to calculate average daytime (06:00 to 20:00 HR) soil temperature for each depth, average daytime (07:00 to 17:00 HR) volumetric soil moisture in the seed furrow (2.5 cm), and daily total (24 h) precipitation.

Expt. 3: Mulch performance in lettuce and onion in Costa Rica. Expt. 3 was conducted at the University of Costa Rica Santa Cruz campus between 13 Sep 2023 and 16 Jan 2024 in the same field as was used for Expt. 2 (adjacent, directly west); therefore, soil properties and weed communities were similar.

The experimental design was an unbalanced completely randomized design with three treatments and two or three replications per treatment (due to limited availability of BCWB material). Treatments included the following: 1) a two-layer paper–PLA composite BCWB (RootThru Weed Barrier) (two replicates); 2) a three-layer PLA–paper–PLA composite BCWB (RootThru™ Max Weed Barrier) (three replicates); and 3) a bare soil, no mulch control (three replicates). In contrast to Expts. 1 and 2, the BCWBs were used like a traditional geotextile fabric whereby the weed barrier was laid on the soil surface, and holes were cut into the barrier to transplant crop seedlings. Each experimental plot was 1.22 m wide by 5.0 m long.

Lettuce ('Sargasso') and green onion [*Allium fistulosum* ('Parade')] seeds were planted on 13 Sep 2023 in greenhouse flats filled with soilless media in an outdoor nursery with intermittent misting, partial shade, and insect net protection. Seedlings were transplanted by hand into the field on 25 Oct 2023 into two rows spaced 30 cm apart with 30 cm between plants within rows. Onions were planted into the west row of each plot and lettuce into the east row (beds were oriented north to south). A single line of drip irrigation tape was placed on top of the BCWB or soil (control), and plots were irrigated daily. Plots were hand-weeded just before transplanting, but no weed control beyond BCWBs was used thereafter. Plants were sprayed on 12 Nov 2023 with a foliar fertilizer (~3 L/ha; 11.5% N, 8% P_2O_5, and 6% K_2O analysis; Bayfolan Forte; Bayer de Mexico, Mexico City, Mexico) and deltamethrin insecticide (~420 mL/ha; decis protech; Bayer CropScience Limited, Cambridge, UK).

Data collection in Expt. 3 included lettuce canopy diameter and onion fresh weight. Lettuce yield data were not collected because plants bolted and produced flowers before the planned harvest dates; therefore, lettuce canopy diameter was used as a proxy for growth and yield potential. Lettuce canopy diameter was determined with analysis of images (ImageJ; Ferreira and Rasband 2012) collected from 1 m above the canopy on 13 Dec 2023 with a 30-cm reference. Onions were harvested on 9 Jan 2024 and weighed fresh to determine yield per plant after removing soil from the bulb.

Statistical analysis. Differences among treatments for lettuce and weeds data from Expt. 1, mulch deterioration data from Expt. 2, and lettuce and onion data from Expt. 3 were evaluated using analysis of variance (Proc GLIMMIX; SAS 9.4; SAS Institute Inc., Cary, NC, USA). For lettuce stand and season-long cumulative weed density data in Expt. 1, treatment was the fixed effect and replicate block was the random effect. Preliminary analysis of weed density data by date revealed no effects of time or time by treatment factors on weed density. For lettuce yield, harvest date and the interaction with treatment were added as fixed effects in a repeated measures analysis. Similarly, for analysis of mulch deterioration in Expt. 2, treatment, date, and their interaction were fixed effects, and replicate block was the random effect in a repeated-measures analysis. Nonreplicated microclimate data from Expt. 2 was plotted over time by treatment but not analyzed. For analysis of lettuce canopy diameter and onion yield data in Expt. 3, treatment was the fixed effect, and replicate block was the random effect. For all analyzes, differences among treatments were determined using Tukey's honestly significant difference test for multiple comparisons and orthogonal contrasts of mean effects with a significance level of $P < 0.05$.

Results and discussion

Expt. 1: Mulch performance in lettuce in Nebraska. The two-layer BCWB reduced weed emergence by 91% to 95% compared with bare soil, but there was no difference between the mulch broadcast and mulch furrow methods (Fig. 2). The level of weed suppression achieved was similar to that observed with a PLA-only BCWB in carrot where weed emergence was reduced 90% to 96% compared with bare soil (Wehrbein et al. 2024). Wehrbein et al. (2024) planted carrots using the mulch broadcast method where the entire BCWB and bed top were covered with compost and six narrow rows of carrot were seeded into the compost. With a paper–PLA composite BCWB, the paper layer is intended to provide important early-season weed suppression, particularly for grass weeds and sedges (Cirujeda et al. 2012). However, it was unknown whether the weed suppressive

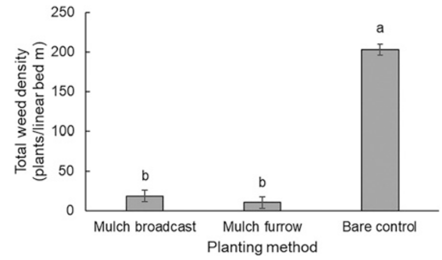

Fig. 2. Total season-long weed density (plants/linear bed (m) among the different planting methods [mulch broadcast, mulch furrow, and bare soil furrow (control)] in Lincoln, NE, USA. One plant per linear bed m = 0.3 plant per linear bed ft = 8201 plants per ha = 3319 plants per acre assuming spacing of 4 ft between bed middles. Error bars are ± 1 standard error of the mean. Different letters above bars indicate significant differences among treatments (*P* < 0.05).

capacity of the paper layer would be compromised when buried fully (mulch broadcast method) or partially (mulch furrow method) below a layer of compost. The tensile strength of Kraft paper generally declines with increasing moisture content (Rhim 2010), and compost applied on top of the BCWB may prevent evaporative loss and retain moisture in the paper layer (Cogger et al. 2008). However, if that occurred, it did not measurably reduce the weed suppressive capacity between planting approaches within mulch (broadcast vs. furrow) or compared with a BCWB without paper (Wehrbein et al. 2024).

Lettuce yield was influenced by the interaction of treatment and harvest date ($P < 0.001$). At the first harvest on 5 Sep, yield was greatest in the mulch broadcast treatment compared with the mulch furrow and bare soil furrow (control) treatments (which were not different from each other; Fig. 3). By the second harvest on 20 Sep, there were no differences in yield among treatments. Combined across both harvests, total yield was greater in the mulch broadcast treatment compared with bare furrow (control), but the mulch furrow treatment was not different from either mulch broadcast or bare furrow (control) (Fig. 3).

Weeds were removed after counting at 9, 21, and 29 d after planting, which helps to explain the lack of weed-induced yield loss in the bare soil furrow (control) treatment compared with the mulch furrow treatment. While PLA-based BCWBs have

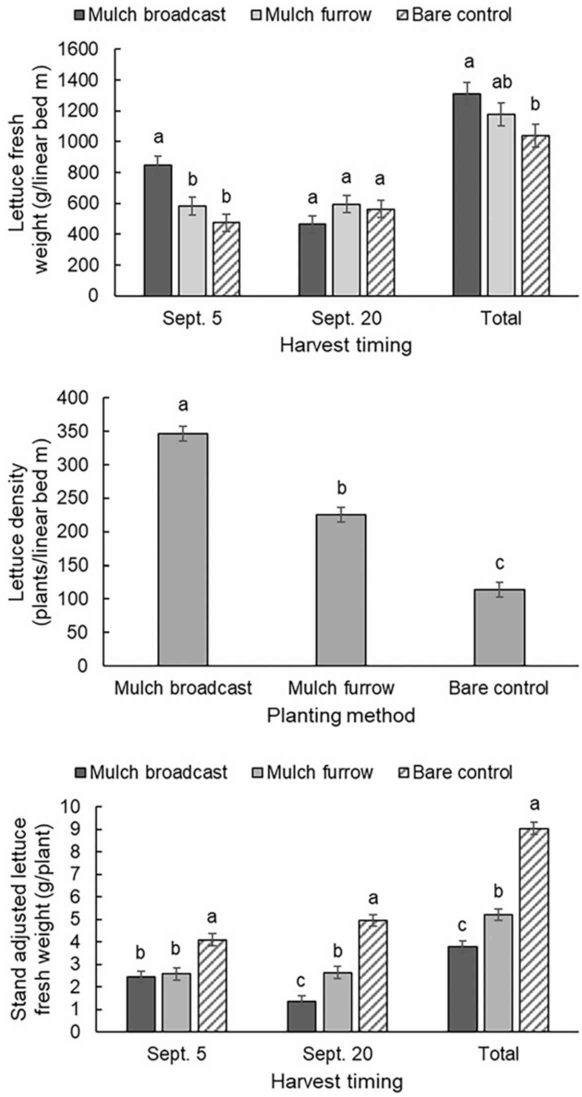

Fig. 3. Lettuce fresh yield weight (g/linear bed m; top), density (plants/linear bed m; middle), and per plant fresh weight (g/plant; bottom) for the mulch broadcast, mulch furrow, and bare soil furrow (control) planting methods at two harvest times and total for the season in Lincoln, NE, USA. One gram per linear bed m = 0.01 oz per linear ft. One plant per linear bed m = 0.3 plant per linear bed ft = 8201 plants per ha = 3319 plants per acre assuming spacing of 4 ft between bed middles. One gram per plant = 0.035 oz per plant. Error bars are ± 1 standard error of the mean. Different letters above bars (within harvest timing for top and bottom figures) indicate significant differences among treatments ($P < 0.05$).

been shown to mitigate extreme soil temperatures, soilborne disease, and soil water loss (Wortman et al. 2015), the lack of yield differences in the absence of weeds suggests that the primary agronomic benefit of BCWBs is weed suppression. Importantly, the lack of yield difference also supports previous findings that crops are not negatively affected by root growth through the BCWB (Tofanelli et al. 2021; Wehrbein et al. 2024). The mulch broadcast treatment increased lettuce yield at the first harvest by 399 ± 75 g/linear bed m (± 1 standard error) compared with the bare soil furrow (control) treatment (79% increase) and by 283 ± 75 g/linear bed m compared with the mulch furrow treatment (45% increase). However, total yield after two harvests was not different between mulch planting methods. Increased yield in the mulch broadcast method compared with the bare soil furrow (control) treatment was likely a function of seeding rates and stand density.

Lettuce stand density was different among treatments ($P < 0.001$), which in turn influenced stand-adjusted per plant lettuce yield across harvest dates ($P < 0.001$). Lettuce stands were lowest in the bare soil furrow (control) treatment and ~2 and 3 times greater in the mulch furrow and mulch broadcast treatments, respectively. Establishment success rate (proportion of seeds planted that emerged) was 83% in the mulch furrow treatment, 74% in the mulch broadcast treatment, and 42% in the bare soil furrow (control) treatment. Wehrbein et al. (2024) saw a similar trend whereby planting carrots onto a PLA-only BCWB (using the mulch broadcast planting method) increased carrot stand density by 88% compared with bare soil. Stand differences can be explained only in part by differences in seeding rate, which was 73% greater in the mulch broadcast treatment (468 seeds per linear bed m) compared with the mulch furrow and bare soil furrow treatments (270 seeds per linear bed m). However, differences in establishment success between the mulch furrow and bare soil furrow treatments suggest the stand density in BCWB plots was likely improved by the tilth of compost relative to ambient soil.

Lettuce seedling emergence is often reduced by soil crusting and high soil mechanical resistance common in clayey soils (Hemphill 1982), and results suggest that planting into compost—with coarse texture and low mechanical resistance—on a BCWB may circumvent this challenge. The gap in stand density between BCWBs and bare soil may also be the result of unintentional thinning that can occur when hand-weeding (Wehrbein et al. 2024; i.e., lettuce seedlings removed concurrently when the roots of a weed were pulled). While the mechanism is uncertain, the gains in seedling establishment on BCWBs represent a proportionate potential reduction in seeding rate and costs for the grower. The trade-off of planting into a soilless media like compost, compared with ambient soil, is that compost does not retain moisture as well due to its comparatively coarse texture. Therefore, compost (or other soilless media) on a BCWB must be irrigated regularly to ensure successful germination and stand establishment (with specific rates dependent on the physical properties and volume of the media).

Inversely proportionate to stand density, per plant lettuce yield was greatest in the bare soil furrow (control) treatment, followed by mulch furrow, and lowest in mulch broadcast treatments, and these differences were most pronounced at the second harvest on 20 Sep (Fig. 3). Reduced plant size in the BCWBs, particularly the mulch broadcast treatment, suggest plants were overcrowded and further highlights the opportunity to reduce seeding rates when planting into soilless media on a BCWB (Robinson 1970). Smaller plant size, but high yield per unit area, in the mulch broadcast planting method suggests this approach may be useful for baby leaf or processing (i.e., shredding) markets where smaller plants are preferred or acceptable. However, broadcast seeding rates should be further studied and optimized to ensure maximum economic return per unit seed when growing for these markets.

Expt. 2: Microclimate and mulch deterioration in Costa Rica. The average daytime (06:00 to 20:00 HR) air temperature between 12 Oct and 13 Dec at the experimental site in Costa Rica was 29.7 ± 0.1 °C (± 1 standard error). Total precipitation during the experiment was 442 mm, and 99% of this precipitation occurred between 12 Oct and 17 Nov (Fig. 4).

Differences in soil water content and temperature between bare soil and the BCWB could not be analyzed statistically because of the lack of replication, but descriptive trends may inform mulch deterioration results and future research. Volumetric water content in the seed furrow (2.5-cm depth) followed precipitation patterns, particularly until 19 Oct when daily irrigation began. With few exceptions, volumetric water content was higher in bare soil furrows compared with compost furrows on the BCWB (Fig. 4), presumably due to the coarse texture and poor water-holding capacity of compost compared with the Alfisol, clayey ambient soil (Rogers 2017). Temperature at 2.5-cm depth in the seed furrow was consistently greater in compost of the BCWB compared with ambient soil, which is likely also explained by the greater porosity and reduced volumetric water content in coarse-textured compost compared with the finer-textured soil (Fig. 5). This is similar to the trends observed by Miernicki et al. (2018) when comparing the physical properties of compost-based raised beds to ambient field soil.

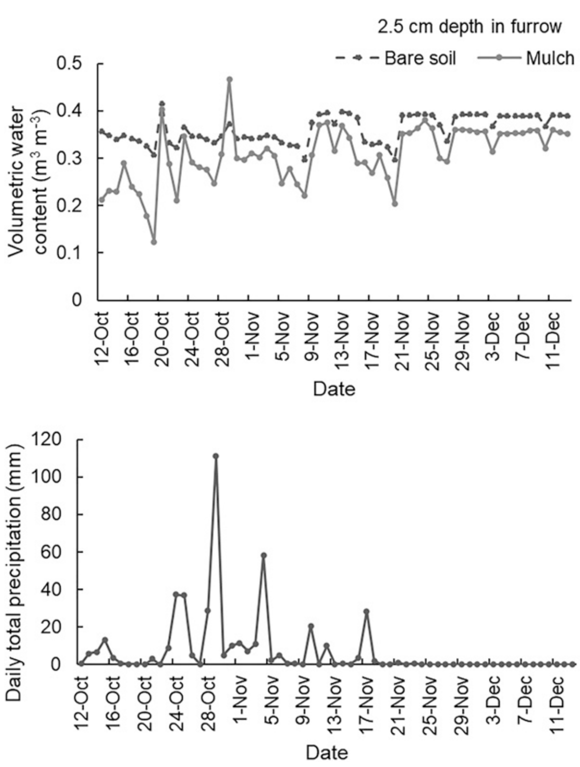

Fig. 4. Volumetric water content ($m^3 \cdot m^{-3}$) at 2.5 cm (0.98 in) depth in furrow of bare soil or compost on top of mulch (top) and daily total precipitation (mm; bottom) in the 2 months after mulch application in Santa Cruz, Costa Rica. 1 $m^3 \cdot m^{-3}$ = 1 $oz^3 \cdot oz^{-3}$. Daily irrigation began on 19 Oct.

At 5 cm below the surface of the soil or BCWB, soil temperature was consistently greater in bare soil compared with the BCWB treatment, and at the 15-cm depth, there was no apparent difference between treatments. Reduced near-surface soil temperatures beneath organic mulches is common (Monks et al. 1997), but previous reports on PLA-only BCWBs found no difference compared with bare soil (Wortman et al. 2015, 2016). This suggests that the addition of a paper layer to a PLA-based BCWB may contribute to a soil cooling effect that is consistent with other paper-based organic mulches (Schonbeck and Evanylo 1998).

Deterioration of the BCWB paper layer was influenced by the interaction of treatment and time ($P < 0.001$). There was no measurable deterioration of the paper layer in the three-layer BCWB between 33 and 64 d after mulch application, but for the two-layer BCWB, visible paper deterioration increased from 0.5% ± 2.0% at 33 d to 12.0% ± 2.0% at 64 d after mulch application (Fig. 6). Similar to results for the two-layer BCWB, Cowan et al. (2016) found that deterioration of paper-only mulch (visible on the bed top above the soil) in Mount Vernon, WA, USA, reached ~10% to 20% by 64 d after mulch application. Moreno et al. (2017) found that above-soil portions of an 85 $g \cdot m^{-2}$ paper-only mulch remained largely intact for at least 90 d after transplanting. However, the portion of the paper mulch covered in soil (i.e., edges of the raised bed) was ~20% deteriorated by 30 d after transplanting and ~45% deteriorated by 64 d after transplanting in Ciudad Real, Spain.

Reduced paper deterioration at 64 d after application in the three-layer compared with two-layer BCWB could be due to the thicker layer of paper (150 $g \cdot m^{-2}$ compared with 75 $g \cdot m^{-2}$) and physical protection of paper from soil provided by the PLA layer in the three-layer BCWB. Moreno et al. (2017) noted that rapid deterioration of paper-only mulches along the edges buried in soil is particularly problematic in windy areas where the mulch can be blown away after soil-anchored portions have deteriorated. However, 64 d after application, the two- and three-layer BCWBs in this study were both fully intact at the buried edges, presumably due to the soil

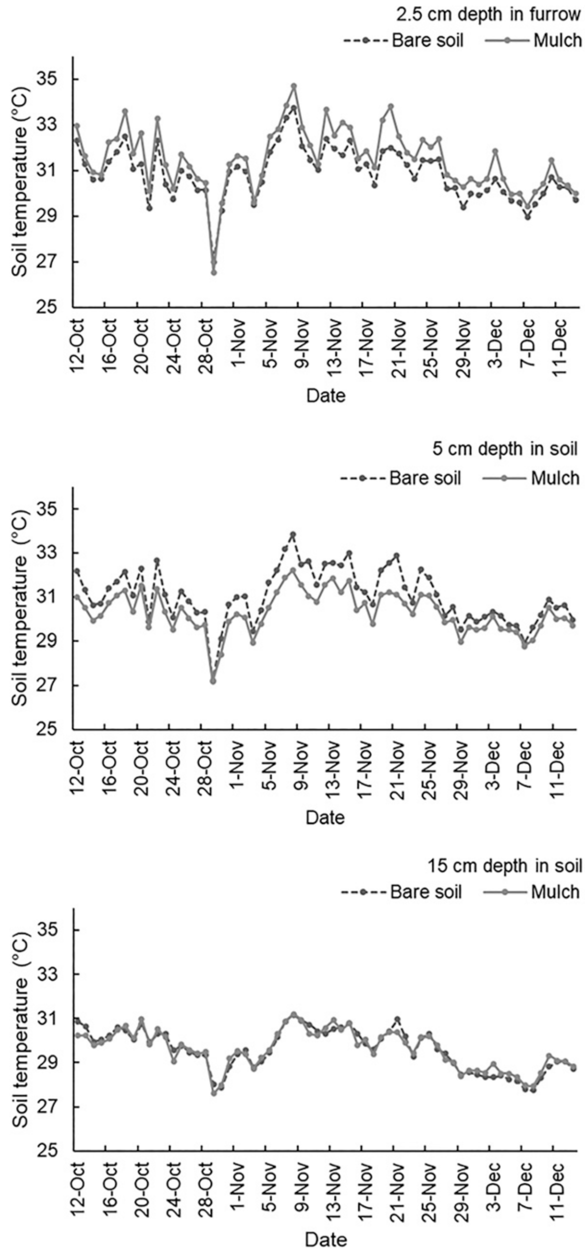

Fig. 5. Temperature in the seed furrow (top), 5 cm below soil and mulch (middle), and 15 cm below soil and mulch (bottom) in the 2 months after mulch application in Santa Cruz, Costa Rica. °F = (°C × 1.8) + 32.

stable PLA layer on top of the paper that serves to hold the paper layer in place even as the paper begins to deteriorate. Polymer-coated papers have successfully been used to slow degradation of paper mulch in soil (Shogren and Rousseau 2005) and the PLA layer may serve a similar function in the tested BCWBs given its previously demonstrated stability in soil compared with paper (Thompson et al. 2019).

Expt. 3: Mulch performance in lettuce and onion in Costa Rica. Lettuce canopy diameter was not different between the two- and three-layer BCWBs, but when pooled together, the BCWBs increased lettuce canopy diameter compared with the bare soil control ($P = 0.03$). Lettuce canopy diameter in bare soil was 97.1 ± 10.9 g compared with 159.2 ± 12.1 g in BCWBs. Trends were similar for onion fresh mass yield, which was not different between the two- and three-layer BCWBs. However, pooled together for contrast with the bare soil control, the BCWBs increased onion fresh mass yield per plant from 29.1 ± 3.7 g in bare soil to 68.1 ± 8.8 g (134% increase) ($P = 0.04$).

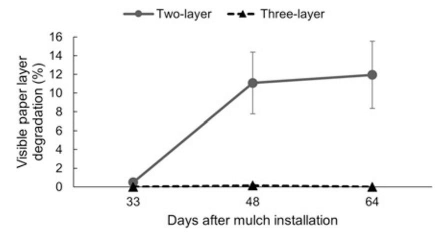

Fig. 6. Visible paper layer degradation (%) as measured by digital image analysis in the two- and three-layer mulches between 33 and 64 d after mulch application in Santa Cruz, Costa Rica. Error bars are ± 1 standard error of the mean.

Crop growth and yield benefits of the BCWBs compared with bare soil were not surprising given that weeds were not removed from the bare soil controls but does highlight the agronomic and economic value of physical weed barriers in the absence of herbicides. Lettuce growth reduction (39%) and onion yield loss (57%) in bare soil compared with BCWBs was slightly greater than the typical yield loss (∼30%) observed in bare compared with mulched soil (Tofanelli and Wortman 2020). The lack of yield differences between the two- and three-layer BCWBs suggests that potential differences in paper-layer deterioration (observed in Expt. 2) did not measurably affect lettuce or onion growth. Depending on weed species and management, the critical weed-free period in lettuce is ∼21 d (Parry and Shrestha 2018) and in onion the critical period of weed control is between 14 and 73 d (de Freitas Souza et al. 2021). When deterioration of a mulch begins after these crop-specific critical thresholds, yield differences are uncommon (Miles et al. 2012).

Conclusions

Two different paper–PLA composite BCWBs were tested in Nebraska and Costa Rica using different seeding methods, including planting seeds directly into compost on the BCWB and growing crops through the weed barrier. In Nebraska, a two-layer paper–PLA BCWB reduced weed emergence by 91% to 95% in lettuce, regardless of whether lettuce was seeded across the entire barrier (broadcast method) or in two wider rows (furrow method). Despite differences in weed emergence, there was no difference in yield between BCWBs and bare soil because weeds were removed regularly after counting; however, the lack of yield differences provides evidence that growing crops on and through BCWBs does not negatively affect crops and that the primary agronomic benefit of BCWBs in lettuce is weed suppression. Lettuce stand establishment and yield was greater in the mulch broadcast method compared with bare soil, although individual plant size was smaller. The loose textured tilth of the compost may have improved seedling establishment, and hand-pulling weeds in bare soil may have inadvertently reduced density of established lettuce.

In Costa Rica, volumetric water content in the seed furrows of compost on BCWBs was less than that in furrows of ambient soil, which highlights an important trade-off of seeding into compost or soilless media instead of soil. Although seedlings may benefit from the loose texture of compost and soilless media (and reduced mechanical resistance during emergence), regular irrigation is important for establishing seeds in the shallow layer of compost used when planting directly on BCWBs. Temperature was greater in the compost furrows compared with furrows in ambient soil, which could accelerate germination of some species [e.g., maize (*Zea mays*)] but stress others (e.g., lettuce), and extreme heat in the seed furrow could be mitigated by regular irrigation. Temperature at 5 cm beneath BCWBs and soil was cooler than bare soil, consistent with soil cooling effects of other biobased and paper mulches, suggesting paper–PLA BCWBs could help mitigate extreme root zone temperatures.

Deterioration of paper in the two-layer BCWB reached 12% by 64 d after application in Costa Rica, but paper in the three-layer BCWB showed no signs of deterioration, which suggests a soil-facing layer of PLA and thicker layer of paper could delay deterioration. Nonetheless, lettuce growth and onion yield in Costa Rica were not different between two- and three-layer BCWBs, suggesting the weed suppression provided by the two-layer BCWB may be adequate for annual crops. However, the three-layer BCWB may have potential for longer-term weed suppression needed for establishment of fruit trees and bushes, windbreaks, perennial flowers, or monocarps such as pineapple (*Ananas comosus*).

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