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Proof of concept for growing lettuce and carrot in a biobased mulch membrane

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Abstract

Manufactured biobased mulch (biomulch) films and fabrics are useful non-chemical weed management tools, but are not typically used for high-density plantings of vegetables such as lettuce (*Lactuca sativa* L.) and carrot (*Daucus carota* L. subsp. *sativus*). However, it may be possible for crop roots to grow through a permeable biomulch membrane. Our objective was to demonstrate the potential for lettuce and carrot to germinate on and grow through biomulch, and assess changes in crop growth and yield. Biomulches included a 100% polylactic acid (PLA) biofabric and a PLA (37%) + soybean meal (63%) biofabric (PLA + SOY). Seeds were placed directly on biomulch and top-dressed with a soil mix or compost. Crop roots grew through the biomulch (despite visible constriction in carrot), and total yields were either the same or greater than those in the no-mulch control. PLA + SOY increased lettuce yield by 72% and also degraded faster than the PLA mulch. Results hold promise for improving weed control and reducing labor in high-density vegetable plantings.

Introduction

Weed control is challenging in high-density vegetable plantings such as looseleaf lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.) and carrot (*Daucus carota* L. subsp. *sativus*), especially for organic growers. Plastic mulch films—commonly used to manage weeds in lower-density organic vegetable plantings such as tomato and pepper—are not feasible because these crops are direct-seeded (not transplanted) and the number of planting holes required would compromise the integrity and function of the mulch. As a result, organic growers manage weeds in high-density plantings with stale-seedbed techniques (Boyd *et al.*, 2006) and cover crops (Lounsbury and Weil, 2015), bioherbicides (Cai and Gu, 2016) and seed meals (Shrestha *et al.*, 2015), flame weeding (Fontanelli *et al.*, 2015) and tillage with harrow and tine weeders (Bond and Grundy, 2001). Unfortunately, most of these methods do not provide the consistent efficacy growers' need and many result in crop injury or reduced stands. As a result, hand weeding is still common in high-density organic vegetable crops (Baker and Mohler, 2015)—so common that lay-down working carts have been commercialized to facilitate the practice (Leinonen and Närkki, 2004).

Manufactured biomulch films and fabrics can suppress weeds, conserve soil moisture and increase yields relative to bare soil (Wortman *et al.*, 2015, 2016). However, biomulch use is currently limited on organic farms because any manufactured mulch product must be: (1) 100% biobased (no petroleum-based feedstocks), (2) 90% biodegraded by soil microbes in less than 2 years if incorporated into soil and (3) manufactured without the use of genetically engineered organisms (Thompson *et al.*, 2019). Paper-based products (e.g., WeedGuardPlus; Sunshine Paper Co., Aurora, CO, USA) are the only commercially available biomulches that currently meet these requirements. However, organic growers can use other biomulch products if the entire mulch can be completely removed from the field after use (i.e., the same requirements that exist for the use of plastic mulch films on organic farms). Removal would be challenging or impossible for highly degraded films, but is feasible for more durable biobased fabrics that are completely intact after one growing season (Wortman *et al.*, 2015).

Similar to plastic mulch films, biomulches have been limited to use with lower-density vegetable plantings such as tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum* L.) and cucumber (*Cucumis sativus* L.). However, the unique physical properties of some biomulches may represent an opportunity for use in higher-density vegetable plantings. Although most agricultural mulch is impermeable by design (e.g., a polyethylene mulch film is impermeable to facilitate chemical soil fumigation), polylactic acid (PLA)-based biofabric mulches are gas and water permeable (Thompson *et al.*, 2019). Previous studies show that this permeability does not compromise weed suppression (i.e., plants cannot grow through

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the mulch from below; Wortman *et al.*, 2015, 2016), but it is not known whether plant roots can grow through this permeable membrane from above.

If crop roots can penetrate and grow relatively uninhibited through the biomulch membrane, then there may exist a unique opportunity to seed and establish vegetables directly on top of the mulch without creating individual planting holes that would jeopardize the integrity of the membrane. If successful, this biomulch innovation for high-density vegetable plantings could eliminate the need for any of the less effective or risky weed management techniques described previously. And beyond weed control, biomulch use in crops such as lettuce and spinach could help to mitigate crop exposure and incidence of soil-borne plant and human pathogens (Sharapov *et al.*, 2016; Gilardi *et al.*, 2018). Moreover, PLA-based biofabric mulches can be manufactured with raw agricultural byproducts such as soybean meal embedded in the fiber matrix. These residues could function as starter fertilizers for seedling roots growing through the membrane and also help to accelerate end-of-life biomulch degradation (Thompson *et al.*, 2019). Our objectives in this proof-of-concept study were to: (1) determine the potential for two direct-seeded, high-density planting vegetable crops to germinate on and grow through prototype-biobased mulch membranes, and (2) measure crop growth changes and yield in response to the prototype mulches.

Materials and methods

A greenhouse trial was conducted at the University of Nebraska—Lincoln in 2019 to accomplish these objectives. We used a completely randomized design with five replicate pots of a 3 × 2 factorial combination of treatments for separate lettuce [*L. sativa* cv. Green Forest (organic and pelleted)] and carrot trials [*D. carota* var. *sativus* cv. Sugarsnax 54 (F1); Johnny's Selected Seeds, Maine, USA]. The first factor was 'mulch' and included two types of prototype-biobased mulch [a 100% PLA biofabric and a PLA (37% by weight) + soybean meal (63% by weight) biofabric (SOY + PLA); 3M Comp., St. Paul, MN, USA; Thompson *et al.*, 2019] and a no mulch control. These products are unlikely to biodegrade by 90% in soil within 2 years. Thompson *et al.* (2019) reported the biodegradation of 23% for PLA and 38% for SOY + PLA after 16 weeks in soil, and degradation seemingly plateaued after 12 weeks suggesting 90% biodegradation within 24 months was unlikely. As a result, use of these products on certified organic farms would require complete removal from the field after use (however, they are certified compostable and could be composted on-farm or at a commercial composting facility). Though partially biodegraded in soil after 16 weeks, the PLA biomulch remains fully intact after a typical field or high-tunnel growing season and mechanical removal is feasible (Wortman *et al.*, 2015, 2016). The SOY + PLA biomulch has not yet been tested in a field environment.

The second experimental factor was 'top-dressing' and included compost or a soil mix. The top-dress layer was used to cover seeds planted directly on top of biomulch treatments to improve imbibition of water and seedling establishment. Compost was derived from forest products, peat, and poultry manure (Garden Soil®, Kellogg Garden Products, Carson, CA, USA). The soil mix was prepared at the university greenhouse facility and included generic peat (38%), top soil (23%), sand (19%) and vermiculite (19%). The soil mix was characterized by lower pH (5.8; 1:1 dilution method), organic matter content (OMC; 4.1%), phosphorus (14 mg kg^{-1}; Mehlich III method) and potassium (207 mg kg^{-1}), but greater nitrate-nitrogen (5.9 mg kg^{-1}) compared to compost (pH = 7.3; OMC = 48.6%; phosphorus = 66 mg kg^{-1}; potassium = 1123 mg kg^{-1}; nitrate-nitrogen = 0.3 mg kg^{-1}). Texture (determined by using a hydrometer) was similar for the soil mix (75% sand, 14% silt and 11% clay) and compost (62% sand, 26% silt and 12% clay).

The soil mix—identical to the mix used as a top-dressing treatment—was used to fill 5 liter black plastic greenhouse pots for all treatments to within 5 cm of the top edge. Mulches were cut in a circle to fit within the top of each pot, and wetted prior to planting to facilitate precise placement of lettuce and carrot seeds. Forty carrot seeds and six lettuce seeds were planted in their respective pots on September 6, 2019 and the appropriate top-dressing treatment was applied to a depth of 1 cm. All pots were watered to field capacity to initiate germination.

During the germination phase (10 days after seeding), greenhouse temperature was set to a continuous target of 18°C. Thereafter, daytime temperature (16 h day^{-1}) was set to a target of 24°C and nighttime temperature to 18°C (8 h day^{-1}). Sodium halide lamps provided supplemental light during daytime hours. All pots were watered daily to field capacity by hand sprinkler. Established seedlings were thinned 3 weeks after planting to reach a final density of 20 carrots and three lettuce plants per pot. Thinning was conducted to achieve spacing of 4 cm between plants in a row and 5 cm between rows for carrot, and 15 cm between plants in a triangle pattern for lettuce. Every pot was fertilized two times per week beginning the fourth week after seeding (i.e., when true leaves began to emerge) with 1 liter of complete liquid nutrient solution (20-10-20 mg L^{-1} NPK; Jack's Professional; J.R. Peters, Inc., Allentown, PA, USA).

Carrots and lettuce were harvested on November 11, 2019. Fresh head weight was recorded for the three lettuce plants in each pot. Root fresh weight, length and diameter (1 cm below base of shoots) were measured for all 20 carrots in each pot. Biomulch from carrot pots was carefully separated from roots and soil using a small brush, air-dried in the lab for 3 weeks, and weighed. Biomulch in lettuce pots could not be recovered for weighing because fibrous roots could not be separated from the mulch matrix. Final biomulch weight was compared to weights collected prior to initiating the study to estimate biomulch degradation during crop growth as percent mulch mass loss (Wortman *et al.*, 2016).

Treatment effects were evaluated with analysis of variance (ANOVA) using the 'glimmix' procedure in SAS (v 9.4, SAS Institute, Cary, NC). Mulch and top-dressing treatments and their interaction were fixed effects in the model and replicate was the random effect. Assumptions for ANOVA, including homogeneity of variance and normally and independently distributed errors, were assessed using the 'univariate' procedure in SAS. The Tukey–Kramer multiple comparisons test was used to assess differences among treatment means at a significance level of $\alpha = 0.05$.

Results and discussion

Crop growth and yield

Mulch treatment affected lettuce yield ($P = 0.002$), but top-dressing and the mulch by top-dressing interaction were not significant. Carrot length, diameter and yield were not influenced by any fixed effects, but the mulch effect was trending toward significance for carrot yield ($P = 0.10$). Averaged across top-dressing

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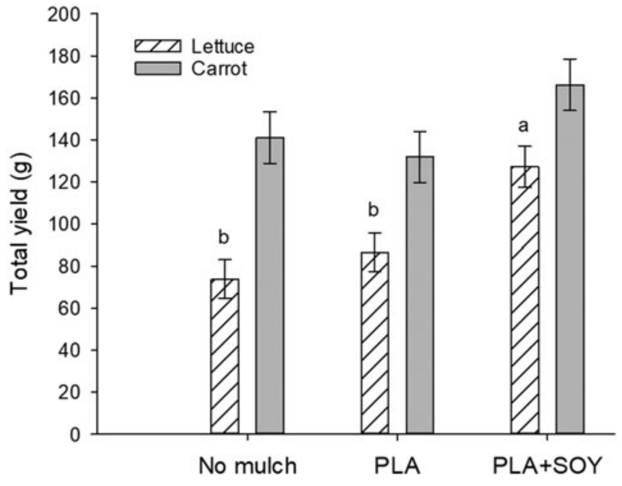

Fig. 1. Fresh lettuce (g per plant) and carrot (g per pot) yield as influenced by the type of biobased mulch barrier beneath the seeded crop. PLA + SOY = polylactic acid-based mulch + soybean meal particles; PLA = polylactic acid-based biofabric mulch. Error bars represent ±1 standard error of the least squares mean. Different letters above bars within a crop indicate differences determined using the Tukey–Kramer multiple comparisons test (α = 0.05).

treatments, PLA + SOY mulch increased lettuce yield (127.2 g) in comparison with PLA mulch (86.5 g) and the no mulch control (73.9 g) (Fig. 1). Carrot yield followed a similar trend, where the PLA + SOY mulch seemed to perform best; however, differences from PLA ($P = 0.095$) and the no mulch control ($P = 0.27$) were not significant.

Because greenhouse pots were void of weeds and watered and fertilized regularly, we did not expect to observe the typical yield benefits of mulch related to weed suppression and soil moisture conservation (e.g., Wortman *et al*., 2015). Thus, the lack of yield differences between the PLA biomulch treatment and the no mulch control successfully demonstrates proof-of-concept for using biomulch in lettuce and carrot. Roots were able to penetrate the permeable biofabric membrane (Fig. 2) and plant growth and yield was not negatively affected by root constriction or any other unforeseen consequences of the mulch. The 72% increase in lettuce yield grown in PLA + SOY compared to the no mulch control was somewhat unexpected because pots were fertilized two times per week beginning approximately 4 weeks after seeding. This result could be explained by two potential benefits of the embedded soybean meal. First, the soybean meal may have served as a starter fertilizer for young crop seedlings because 0.42 g N, 0.06 g P and 0.12 g K were available within the SOY + PLA biomulch placed in each pot [average initial biomulch weight was 9.5 g (63% soybean meal by weight), and embedded soybean meal had a guaranteed analysis of 7-1-2 NPK]. Secondly, microbial degradation of embedded soybean meal would have helped to degrade and reduce molecular weight of surrounding PLA polymers (Thompson *et al*., 2019). The combined result would be larger pores for root growth through the biofabric membrane, and also reduced material strength of remaining PLA that would help mitigate root constriction. Liu and Gao (2018) demonstrated a similar yield benefits of a biobased mulch manufactured from citric acid fermentation wastes; pak choi (*Brassica chinensis* L.) yield was greater in the biomulch in part because nutrients in the mulch were slowly mineralized during crop growth.

Although total carrot yield was not affected by biomulch, visible root constriction and resulting esthetic changes (Fig. 2) would reduce the fresh market value for this crop. For example, U.S. Extra No. 1 carrots must be '…clean, fairly well colored, fairly smooth, well formed…' (USDA, 1965). The lack of yield difference between PLA and no mulch suggests root constriction had mostly esthetic (and eventually marketing) consequences, but constriction may help explain the muted yield benefit of carrot in PLA + SOY mulch. Because the phloem is found near the perimeter of the carrot root (just inside the periderm and outside of the vascular cambium), constriction from the biomulch fibers could have reduced the translocation of photosynthetic resources from shoots to roots. Alternatively, carrots may have been less responsive than lettuce to the embedded soy particles because nitrogen fertilization typically favors shoot relative to root growth (Wortman and Dawson, 2015). Future prototype biomulch can be modified to reduce material strength (without sacrificing weed control efficacy), which would reduce or eliminate the negative physiological and esthetic outcomes observed in carrot.

There was no difference in lettuce or carrot yield between the soil mix and compost used to top-dress seeds and biomulch. This was somewhat surprising given differences in chemical properties (e.g., soil mix had greater nitrate, but compost had greater P and K); nonetheless, results suggest growers using this biomulch system for high-density plantings would have flexibility in choosing compost or other substrates to cover seeds without worry of compromising the demonstrated benefits of the mulch. Using a substrate free of viable weed seeds (e.g., certified compost) will be critical to the success of this system because, as was demonstrated by the crops in this study, weed roots could grow through the biomulch membrane from above.

Biomulch degradation

Differences in biomulch degradation rates among mulch types and top-dressing treatments have production system-specific implications. For non-certified or conventional growers, degradation during crop growth is acceptable or even desirable because the biomulch can be incorporated in soil at the end of the season. If the integrity and function of the mulch is not compromised, then biodegradation during the growing season may facilitate end-of-season mechanical shredding and soil incorporation and further accelerate biodegradation in soil. For certified organic growers, biodegradation during crop growth is less desirable because organic regulations require that, for these specific products, the entire intact mulch be removed at the end of the season; rapid degradation could complicate that process.

Mulch degradation during carrot growth was influenced by the interaction of mulch and top-dressing factors ($P = 0.04$). Mulch mass loss was greatest when PLA + SOY mulch was combined with the compost top-dressing treatment (38.7 ± 2.2%; ±1 standard error), followed by PLA with compost (27.1 ± 2.2%) and PLA + SOY with soil mix top-dressing (25.2 ± 2.2%), and lowest in PLA with soil mix top-dressing (4.1 ± 2.2%). Enhanced degradation of PLA + SOY is consistent with results of Thompson *et al.* (2019) where biodegradation of the same prototype PLA + SOY biomulch was greater than that of the PLA-only mulch as early as 2 weeks after soil incorporation. This difference in biodegradation can be explained in part by the C:N of each mulch—14:1 for PLA + SOY and 1692:1 for PLA—because C:N can be a good predictor of microbial decomposition rates (Eiland *et al*., 2001). Within each mulch type, compost increased degradation; so although compost does not appear to affect crop yield in this system, it could help to speed biomulch

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Fig. 2. Harvested carrots (top left) and root architecture (top right), and harvested lettuce (bottom left) and root architecture (bottom right) after direct-seeding onto the PLA (carrot) or PLA + SOY (lettuce) biofabric mulch.

degradation in soil for conventional or non-certified organic growers planning to leave the biomulch in the field at the end of the growing season. However, certified organic growers who need to remove the biomulch from the field would be advised to use PLA mulch paired with the soil mix top dressing because the biomulch was minimally degraded and fully intact at the end of the experiment.

Conclusions

Results of this study demonstrate proof-of-concept for seeding high-density vegetable crops on top of a permeable-biobased mulch membrane. Roots of lettuce and carrots successfully grew through the mulch, and total yields were either the same or greater than those in the no mulch control. In the proposed biomulch system, growers will make a raised bed and lay the biomulch, place seeds on top of the biomulch (e.g., via broadcast-, air- or drop-seeder) and top-dress with a locally available, certified compost. Crops could then be harvested using typical methods, or the biomulch and crops could be removed in manageable pieces (e.g., Fig. 2) from the field and transported to another location for further processing of produce (e.g., a climate-controlled wash-pack facility) and the biomulch (e.g., composting). The next step in the iterative development of this prototype biomulch innovation will include field testing to determine agronomic performance, potential for reduced incidence of pathogens, and profitability compared to the current mulch-free status quo.

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