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Hydromulch Maintains Strawberry Yield, Fruit Quality, and Plant Nutrition across Two Contrasting Environments

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Abstract. **Plastic mulches made from nonbiodegradable polyethylene (i.e., "PE mulch") are an integral tool for organic and conventional strawberry (*Fragaria ×ananassa*) production due to their ability to optimize soil and crop microclimates, suppress weeds, and promote overall yield and fruit quality. Unfortunately, PE mulch is primarily single-use and seldom recycled, leading to large volumes of plastic waste, with some of the plastic mulch fragments residing in the soil or polluting the surrounding agroecosystem. Although soil-biodegradable plastic mulches are a promising mulch technology that aims to reduce waste generation, no commercial products are available that meet the National Organic Program's requirements. Hydromulches are an alternative mulch technology that is sprayable and can be formulated to meet organic requirements, but they have undergone limited testing. The objective of this study was to evaluate the effects of various hydromulch formulations on yield, fruit quality, and tissue nutrient status of day-neutral strawberries grown in two diverse environments. Hydromulches made with various formulations of paper, guar gum, or psyllium tackifiers were compared with PE mulch in Northwest Washington and North Dakota in 2022. Few treatment effects were observed throughout the experiment, and both strawberry yield and fruit quality were maintained. Slight variations in tissue nutrient concentrations were observed but not attributed to hydromulch treatments. Information resulting from this project demonstrates hydromulches maintain crop productivity and quality. Future research should evaluate the ability of hydromulches to suppress a spectrum of weed species, impacts on soil health, and economic viability.**

Polyethylene (PE) mulch suppresses weeds, improves crop microclimates, lowers evaporative water loss, and increases crop yields and potentially quality (Amare and Desta 2021; Food and Agricultural Organization of the United Nations 2021; Li et al. 2018). The global mulch film market used more than 2 million metric tons of plastic mulch in 2018 (Le Moine and Ferry 2019), with linear low-density PE (LLDPE) and high-density PE (HDPE) being the two most common polymers used to make mulch film (Fleck-Arnold 2000; Sarkar et al. 2018). By 2030, the global mulch film market is poised to reach slightly more than 3 million metric tons per year (Le Moine and Ferry 2019). Despite the benefits of PE mulch, it can be detrimental to the environment due to plastic pollution (Li et al. 2022; Liu et al. 2014; Madrid et al. 2022). PE mulch is a significant source of macro- and microplastics in agricultural soils due to their propensity for tearing, rendering complete removal challenging (Li et al. 2022). These plastics have been shown to accumulate in surface soils and migrate to the subsoil, where they can pollute the surrounding environment including soil, water, and air (He et al. 2018; Li et al. 2022).

PE mulch is generally single-use, and because PE does not biodegrade, it must be removed from fields every season (Li et al. 2022; Velandia et al. 2019). This results in large amounts of single-use plastic waste, which often cannot be recycled due to contamination from soil and organic matter (Levitan and Barros 2003; Madrid et al. 2022; Moore and Wszelaki 2016). Recycling efforts are further confounded by the lack of facilities with adequate equipment to economically clean and process plastic mulch, resulting in the cost of recycling PE mulch being greater than its market value once recovered (Madrid et al. 2022; Moore and Wszelaki 2016). The confluence of these factors results in most used PE mulch being burned, buried, landfilled, or stockpiled (Goldberger et al. 2019; Moore and Wszelaki 2016).

Organic agriculture in the United States depends heavily on PE mulch for weed management and is not immune to the environmental problems associated with waste management. Unfortunately, the organic industry in the United States has few alternatives for effective weed management, and most commercially available soil-biodegradable plastic mulch (BDM) alternatives do not meet the National Organic Program's (NOP) requirements for organic agriculture. The NOP currently prohibits the use of BDM not composed of 100% biobased ingredients, which is determined by ASTM D6866 and is in NOP rule § 205.3. At the time of writing, BDMs on the market range from 10% to 40% biobased content (Giannotti 2017; Miles et al. 2017; Organic Materials Review Institute 2015). Also outlined under NOP rule § 205.3 is that BDM must meet compostability specifications (i.e., ASTM D6400, ASTM D6868, EN 13432, EN 14995, or ISO 17088), and degrade at least 90% within 2 years of incorporation based on ISO 17556 or ASTM D5988 standards [US Department of Agriculture (USDA) 2024a]. A similar ban has been placed on nonapproved synthetic substances, such as substances derived from genetic modification, which are outlined in NOP rule § 205.601(b)(2)(iii) (USDA 2024b). At the time of publishing, no commercially available BDM meets these specifications for use in US organic agriculture.

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Data presented in this study and others are openly available in the North Dakota State University Repository under the "MulchH2O Project Data" project title, accessible at https://library.ndsu.edu/ir/handle/10365/33038.
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Organic agriculture requires new and innovative mulch technologies that satisfy the NOP's requirements and provide horticultural benefits comparable to PE mulch. Hydromulch (also known as "hydramulch") is an innovative mulch alternative that is sprayable and can be manufactured to be soil-biodegradable using 100% biobased feedstocks and additives allowed in organic agriculture. The primary ingredients in hydromulch include polysaccharide feedstock material(s) made primarily of cellulose, water, and tackifier. Paper is one cellulosic feedstock source, but it must be recycled and not contain glossy or colored inks to be allowed for use in certified organic agriculture, per NOP rules § 205.601 and § 205.2, respectively (USDA 2024b, 2024c). Other potential cellulosic feedstock sources may come from nonpaper virgin raw materials such as lignocellulosic biomass. Hydromulches have the potential to address all the environmental and certification barriers of traditional PE mulch and commercially available BDM while preserving the benefits associated with their use. Although information on the application of hydromulch in diverse agricultural systems is limited, a similar technology called "hydroseeding" has been used for turfgrass establishment since at least 1967, and ecological restoration since 1975 (Lum et al. 1967; Naveh 1975). Note that commercially available hydroseeding substrates typically contain compounds that promote seed germination and growth and are unlikely to be suitable for hydromulching applications.

The objective of this experiment was to evaluate the effects of various hydromulch formulations on yield, fruit quality, and tissue nutrient status of day-neutral strawberries (*Fragaria ×ananassa*) grown in two diverse environments. These metrics are essential to assess due to the scarcity of published data on the effectiveness and suitability of hydromulch in strawberry production systems. Results on weed data, percent canopy cover, and plant biomass are discussed in Ahmad et al. (2024). Information resulting from this project will contribute toward developing hydromulch as a tool for organic as well as conventional producers seeking to reduce plastic waste generation while maintaining the horticultural benefits of PE mulch.

Materials and Methods

Site characteristics. Two field experiments were conducted in 2022 at two locations with contrasting environmental and soil conditions: the Washington State University (WSU) Northwestern Washington Research and Extension Center (NWREC) in Mt. Vernon, WA, USA (lat. 48°26′28.9″N, long. 122°23′44.1″W) and the Dale E. Herman Research Arboretum near Absaraka, ND, USA (lat. 46°59′30.1″N, long. 97°21′14.0″W). The Köppen-Geiger climate classification at the Washington (WA) location is warm-summer Mediterranean (Csb) with mild, wet winters and cool, dry summers (Beck et al. 2018). Conversely, the Köppen-Geiger climate classification at the North Dakota location is warm-summer humid continental (Dfb) with high variation in temperature depending on both season and time of day. Precipitation is medium to low, and winds are generally high across the region. In the Washington field, the soil is a silt loam, characterized by mixed nonacidic mesic Aquic Xerofluvents. The slope of the field is 0% to 3%, with a stratified substratum of loam, sand, and fine sand (NRCS Soil Survey Staff 2023). The soil at the North Dakota location is a Warsing sandy loam complex, comprised of a fine-loam over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls.

Experimental design. The experimental design at both locations was a randomized complete block with six mulch treatments and four replicates. Raised beds in Washington were formed using a mechanical bed shaper (2600; Rain-Flo Irrigation LLC., East Earl, PA, USA). The resultant beds were 0.6 m wide, 0.3 m tall, and spaced 4.3 m apart in the center. Drip tape with 20-cm emitter spacing and 4.2 L per min per 100-m flow rate (T-Tape 508-08-340; Rivulis, Kibbutz Gvat, Zaf, Israel) was buried to a depth of 2.5 cm; however, due to technical difficulties with the mulch layer, the drip tape was higher in some areas. Beds in North Dakota were also formed using a mechanical bed shaper (MRB-448; Berry Hill Irrigation Inc., Buffalo Junction, VA, USA). Drip tape with 10.2-cm emitter spacing and 3.8 L per min per 100-m flow rate (Med Flow TDE804100; DripWorks, Willits, CA, USA) was buried at a depth of 6.4 cm during mulch application. The resulting beds were 0.9 m wide, 0.1 m tall, and spaced 4.6 m on center. Weeds within field borders and alleyways were maintained using mechanical cultivation at both locations.

Treatment application. To ascertain in-field performance for various tackifier sources and concentrations, a total of five hydromulch treatments were evaluated alongside a PE mulch control using paper (25.4-μm thickness) as the cellulosic feedstock for the hydromulch treatments. Treatments in both locations included 1) paper only (no tackifier; 135 g paper: 3.8 L water), 2) paper with 2% psyllium tackifier (133 g paper: 3.8 L water), 3) paper with 6% psyllium tackifier (127 g paper: 3.8 L water), 4) paper with 2% guar gum tackifier (133 g paper: 3.8 L water), and 5) paper with 6% guar gum tackifier (127 g paper: 3.8 L water). All hydromulch formulations were selected based on previous experiments that evaluated multiple formulations' material properties (Durado et al. 2024). The feedstock paper source was ULINE newsprint paper (S-638; Uline, Pleasant Prairie, WI, USA). Note that obtaining approval from an organic certifier for any hydromulch formulation used in certified organic production is essential. Failure to do so could jeopardize the farm's organic certification.

The hydromulch application system in Washington (Fig. 1A) was custom-built and included a 78.7 × 104.0 cm stainless-steel platform with a 3-point hitch, flextube, 5.1-cm PVC tubing, 208-L plastic barrel, two 5.1-cm PVC valves, and a 2.5-cm, 80° brass flat fan spray nozzle with 219.6 maximum L/min (VeeJet type nozzle with custom aperture). The mulcher was powered by a 212 cm^3 gasoline semitrash water pump (Predator™ 63405;

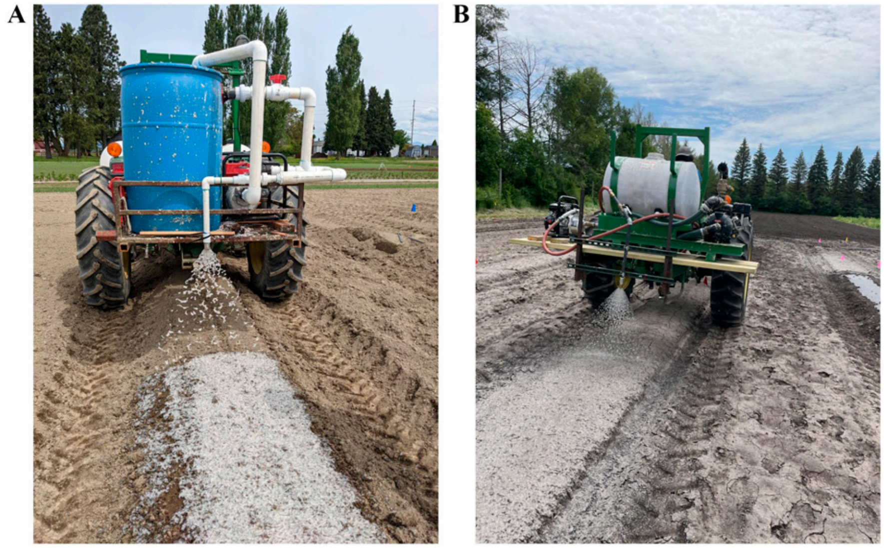

Fig. 1. Hydromulch applicator system in Washington State (**A**) and North Dakota (**B**) applying hydromulch slurry to pre-formed raised beds, 2022.

Harbor Freight Tools®, Calabasas, CA, USA) and the applicator was made with a dual-loop system composed of PVC piping. The first loop allowed for circulation of the hydromulch slurry, and the secondary recirculation loop continued to mix the slurry and avoid sedimentation in the bottom of the tank. Additionally, the secondary recirculation loop allowed for two plastic valves to better control output flow.

The system in North Dakota (Fig. 1B) was built using a hydroseeder (HS-150; Turbo Turf, Beaver Falls, PA, USA), with a 1.9 cm, 80° brass flat fan nozzle (SN-80400; Turbo Turf, Beaver Falls, PA, USA), a clear water pump (Ironton 60729; Northern® Tool + Equipment, Burnsville, MN, USA), and wooden platform fabricated at the NDSU Service Center. The hydroseeder had a 205-cm^3 centrifugal pump powered by a recoil start engine (SE2UL E6VCP; Briggs & Stratton, Milwaukee, WI, USA). However, this pump was found to be overpowered for hydromulch application and created unwanted soil mixing during application. For this reason, a 2.54-cm diameter hose was used between the outlet at the bottom of the tank and the inlet of the clear water pump, resulting in low enough pressures to apply hydromulch with minimal mixing with soil.

In Washington, preweighed paper sheets were soaked for 24 h in water before being macerated into a slurry by hand using a combination of implements, including cabbage splitters, pitchforks, and shovels. The resultant hydromulch slurry with the target amount of paper and water was then pumped into a 208-L plastic barrel and circulated through the application system for several minutes so the pump's impeller could further break down the hydromulch into a homogeneous slurry. The tackifier was then added to the tank to reach the desired concentration, and the slurry was recirculated again until the tackifier was fully incorporated and ready to be applied. In North Dakota, paper was first shredded using a paper shredder (Bonsaii® EverShred c149-d; Bonsaii®, Flowery Branch, GA, USA). Next, 35 L of water was added to a 208-L plastic tank, the hydroseeder centrifugal pump was activated, and the appropriate amount of shredded paper for each treatment was slowly added to the tank where the pump would further break it down. It was important to add this material slowly to prevent pump clogging. The requisite amount of tackifier was then premixed in an 18.9-L bucket using a drill and paint mixer. Once a solution was formed, the tackifier was poured into the slurry and mixed until a homogenous slurry formed.

The treatment application was completed on 1 Jun 2022 in Washington and 28 Jun 2022 in North Dakota. Hydromulch application was completed by driving a tractor over the top of pre-formed raised beds with hydromulch applied by directly spraying the treatment onto the top of the beds and drip tape (Fig. 1). Three and two passes were required at Washington and North Dakota, respectively, with an application rate of 4535 kg dry matter per ha and a target thickness of 2 to 7 mm at both locations. The PE mulch control was applied by hand at the time of raised bed formation in both locations.

Bareroot, day-neutral 'Albion' plants were transplanted by hand through the mulch layer on 8 Jun 2022 and 29 Jun 2022 in Washington and North Dakota, respectively. Plants were received dormant and kept in cold storage until planting. Spacing was staggered with 30 cm between plants within a row and 24 cm between staggered double rows, resulting in 6 to 8 plants per subplot. All plants in each subplot were harvested for yield data. In Washington, a bulb digger was used to create planting holes through the mulch layer but did not penetrate deeply in the soil. In North Dakota, notched metal bars were used to create holes in mulch layers. At both locations, strawberry plants were inserted through the mulch layer using a notched metal bar, ensuring good contact between the roots and soil.

Although every effort was made to have identical treatments and application technology across locations, mulch preparation and application differences were unavoidable. These differences stem from using different mulch applicators, with WSU's mulch applicator necessitating soaking and some pulping of the paper by hand before the applicator could further break down the mulch. In contrast, North Dakota's pump was robust enough to tank mix ingredients, eliminating the need for soaking or hand pulping of paper.

Plant management. Both locations were managed similarly using organic practices and had pre-plant soil testing done to ascertain baseline soil pH, organic matter levels, and macro- and micronutrient ranges. Minor differences in soil micronutrient testing include Washington testing for chlorine, omitting aluminum, and testing for soluble salts instead of sodium. In North Dakota, aluminum was tested instead of chlorine, and sodium was tested instead of soluble salts. Pre-plant soil test results were used to inform fertilizer applications for day-neutral strawberry production (Dixon et al. 2023). Twenty soil cores were collected across the experimental location in Washington whereas 48 soil cores were collected in North Dakota. Both locations were sampled to a depth of 30 cm using a 2-cm-diameter soil probe and composited. Soils were then analyzed at local soil testing laboratories (Washington: Simply Soil Testing, Burlington, WA, USA; North Dakota: Agvise Laboratories Inc., Northwood, ND, USA). Granulated feather meal (11–0–0; Nature's Intent; Pacific Calcium Inc., Tonasket, WA, USA) was broadcast applied using a drop spreader (6506T16; Gandy, Lovington, NM, USA) at a rate of 27.2 kg per ha on 31 May 2022 in Washington. The pre-plant fertilizer in North Dakota was 2–3–4, aerobically composted chicken manure (ChickNPoo; Pearl Valley Farms, Inc., Road Pearl City, IL, USA) and was broadcasted by hand to achieve a rate of 61.65 kg per hectare on 24 Jun 2022. At both locations, these dry amendments were then incorporated into the soil by rotary tillage before raised bed formation and hydromulch application. In Washington, plants were fertigated weekly post planting using a liquid fertilizer derived from sugar beet extract and corn steep liquor (TRUE 4–2–2; True Organic Products, Inc., Spreckles, CA, USA) diluted in 10 parts water at a rate of 5.7 kg N per ha. In North Dakota, the same fertilizer was applied twice a month at a rate of 11.4 kg N per ha. Fertigation began on 27 Jun (19 d after planting) in Washington and 12 Jul (13 d after planting) in North Dakota. Fertigation ended on 10 Oct 2022 in Washington, and on 9 Sep 2022 in North Dakota. Additionally, blossoms were removed for 6 weeks at the onset of bloom and runners were removed for the duration of the experiment every 1 to 2 weeks.

Yield and fruit quality data collection. Yield data were collected by hand harvesting fruits from weed free subplots one to two times per week throughout the duration of the harvest season depending on weather and crop load. In Washington, harvest began on 27 Jul 2022 and ended on 17 Oct 2022. In North Dakota, harvest began on 1 Sep 2022 and ended on 13 Oct 2022. Harvested fruit were transported to a laboratory, stored in a refrigerator, and were graded and weighed within 24 h of harvest. Marketable and unmarketable fruit weights were recorded by plot. After collecting yield data, the fruits were frozen for future quality analysis. Unmarketable fruit was categorized based on size (fruit ≤20 mm were culled), visual or developmental defects, and damage from pests or diseases. A 20-berry subsample was collected weekly per plot and frozen at −23 °C for later fruit quality analysis. Strawberries were thawed at room temperature (≈21 °C) and processed into a puree using a kitchen-grade blender operated for 30 to 60 s before fruit quality analysis. A juice solution devoid of solids was obtained by straining the puree through a fine mesh kitchen strainer and then two layers of cheesecloth. Juice total soluble solids (TSS), titratable acidity (TA; as percent citric acid), and pH were subsequently measured in triplicate. In Washington, TSS was measured using a digital refractometer (HI96801; Hanna Instruments, Smithfield, RI, USA). Using a digital titrator, TA was determined after titrating juice to a pH of 8.1 using 0.1 N sodium hydroxide (HI84532; Hanna Instruments). In North Dakota, a digital refractometer (MA871; Milwaukee Instruments, Rocky Mount, NC, USA) was used to measure TSS, while juice TA was measured by diluting a 1-g sample of strawberry juice with 49 g of deionized water, mixing thoroughly, and then measuring acidity using a TSS-Acidity hybrid meter (PAL-BX|ACID F5; ATAGO, Tokyo, Japan). At both locations, initial juice pH was measured before titration using an ATAGO pH meter (PAL-pH 4311; ATAGO).

Leaf tissue nutrient content. The most recent, fully expanded leaves with petioles attached were sampled for macro- and micronutrient assessment at peak vegetative growth, which was 1 Aug 2022 in Washington and 22 Aug 2022 in North Dakota (Dixon et al. 2023). Leaves were sent to Brookside Laboratories (New Bremen, OH, USA) to quantify macro- and micronutrients using methods outlined in Soil, Plant, and Water Reference methods for the Western Region (Gavlak et al. 2005; Kingston and Jassie 1986; Sah and Miller 1992). Samples were dried in a forced-air oven for 1 to 2 h at 130 °C and then dried overnight at 60 °C before being ground before digestion. Samples were then analyzed for N, P, K, Mg, Ca, S, B, Fe, Mn, Zn, Al, and Na. All nutrients other than N were processed using HNO_3 and H_2O_2 in a closed Teflon vessel, digested in a microwave digestion system (CEM Mars; CEM Corporation, Charlotte, NC, USA), and analyzed on an ICP emission spectrometer (Thermo 6500 Duo ICP Spectrometer; SpectraLab, Markham, Canada). Nitrogen was analyzed using a combustion analyzer (1500 mk I; Carlo Erba, Cornaredo, MI, USA).

Environmental data. Environmental data including relative humidity, air temperature, and precipitation were collected every 15 min from nearby university enviroweather stations (NDAWN and WSU AgWeatherNet). The Washington weather station was 0.7 km away from the research plot, and in North Dakota the weather station was 29 km away in Prosper, ND, USA. Soil moisture and temperature below the mulch treatments were recorded every 15 min using data loggers (Zentra ZL6; Meter Group, Pullman, WA, USA) installed in the third replicate block 5 cm away from irrigation emitters for each treatment. Sensors were installed horizontally at a depth of 10 cm in Washington, 15 cm deep in North Dakota, and were 5 cm away from strawberry crowns at both locations. The sensor was placed 5 cm deeper in North Dakota due to a lack of soil aggregation, which caused sidewalls of holes to collapse above the sensor, leading to soil disturbance, which may have impacted soil moisture readings per the manufacturer. All environmental data were averaged by month and were not statistically analyzed due to lack of replication.

Statistical analysis. Analysis of variance (ANOVA) was performed using R [R ver. 4.3.3 (R Core Team 2023)]. Fixed effects included mulch treatment and location. Replicate was combined with location into one column and used as a random effect. Response variables included marketable and unmarketable yield, fruit quality variables, and leaf tissue nutrients. Simple main treatment effects and interactions between treatment and experimental location were considered significant at $\alpha = 0.05$. Data are presented by location when there was a significant treatment by location interaction. Normality and homogeneity of variances were assessed through the Shapiro-Wilk test ($W > 0.90$). A least-squares mean option was used using a two-way ANOVA. For estimates and tests of significance, a Tukey's honestly significant difference post hoc analysis was used with adjustments for multiple comparisons. Due to

Table 1. Yield and fruit quality [total soluble solids (TSS, %), titratable acidity (TA; as percent citric acid), and pH] of 'Albion' day-neutral strawberry grown with various hydromulch (HM) treatments in Washington and North Dakota, USA, 2022. Washington's harvest began on 27 Jul 2022 and ended on 17 Oct 2022. North Dakota's harvest began on 1 Sep 2022 and ended on 13 Oct 2022.

	Yield (g/plant)		Fruit quality		
Treatment[i]	Marketable[ii]	Unmarketable[ii]	TSS (%)[iii]	TA (%)[iii]	pH[iii]
Washington					
HM, 2% psyllium husk	192.8	12.5	10.2	1.15	3.79
HM, 6% psyllium husk	235.1	18.8	10.3	1.15	3.75
HM, 2% guar gum	195.0	9.9	10.2	1.14	3.76
HM, 6% guar gum	216.6	16.7	10.1	1.15	3.71
HM, no tackifier	206.6	16.8	9.9	1.15	3.79
Polyethylene (control)	193.7	16.8	10.4	1.16	3.76
North Dakota					
HM, 2% psyllium husk	30.1	15.5	10.5	1.02	4.03
HM, 6% psyllium husk	43.2	16.8	10.4	1.01	4.11
HM, 2% guar gum	42.8	8.6	10.2	0.79	4.13
HM, 6% guar gum	60.2	26.5	10.0	0.97	4.18
HM, no tackifier	28.1	11.4	10.8	1.02	3.87
Polyethylene (control)	0.8	3.4	7.2	0.92	4.04
Significance					
Treatment[iv]	0.553	0.719	0.777	0.793	0.739
Washington	0.972	0.380	0.679	0.932	0.052
North Dakota	0.107	0.743	0.174	0.868	0.066
Location	<0.001	0.642	0.216	0.002	<0.001
Location × treatment	0.427	0.061	ND[v]	ND[v]	ND[v]

[i] Treatments include hydromulch formulations made with 2% or 6% psyllium or guar gum tackifier, no tackifier, and a polyethylene mulch control.

[ii] Yield data were analyzed with least square means analysis of variance and Tukey's honestly significant difference.

[iii] Juice TA, TSS, and pH were analyzed nonparametrically using Kruskal-Wallis due to nonnormality.

[iv] Treatment statistics were analyzed across locations.

[v] Fruit quality does not have statistics for location × treatment interactions due to a lack of statistically meaningful non-parametric two-way analysis.

Table 2. Average monthly air temperature, total precipitation, and relative humidity near hydromulch experiment locations in Mount Vernon, WA, USA and Prosper, ND, USA, 2022. Data from Washington were collected from a Washington State University AgWeatherNet station 0.7 km from the experimental field location and North Dakota data were collected from a NDAWN station 29 km from the experimental field location in Prosper, ND, USA.

	June	July	August	September	October
Washington					
Average temp. (°C)	15.1	17.7	18.2	15.0	10.9
Total precip. (mm)	79.0	7.6	5.6	0.5	86.1
RH (observed, %)	78.2	76.1	76.7	76.1	84.7
North Dakota					
Average temp. (°C)	19.4	21.1	19.4	15.0	7.8
Total precip. (mm)	84.6	39.9	102.4	37.6	3.8
RH (calculated, %)	58.6	75.8	81.1	69.4	60.3

nonnormality, fruit quality data, including TSS, TA, and pH, was analyzed within locations nonparametrically using a Kruskal-Wallis test, and where significance occurred, a Dunn test was performed. Similarly, due to a lack of statistically robust nonparametric two-way analysis, statistics for location by treatment interactions are absent from fruit quality measurements.

Results and Discussion

Hydromulch treatments maintained yield across both locations when compared with the PE mulch control with no differences detected for both marketable or unmarketable yields (Table 1). Interestingly, yields were maintained despite greater weed density in hydromulch treatments according to Ahmad et al. (2024), who separately published weed suppression and mulch performance results from the same experiment. A location effect was observed for marketable yield with North Dakota on average having 83% lower yield than Washington. Air temperatures in North Dakota were on average 3.9 °C warmer than Washington during critical fruiting periods in June and July (Table 2). These elevated temperatures may have led to decreased yields in North Dakota. Previous research has shown strawberry fruit yields and root growth are diminished as daytime temperatures increase >20 °C with days >30 °C in particular showing diminished overall plant health and increased unmarketable yield (Balasooriya et al. 2018; Kadir et al. 2006; Wang and Camp 2000). According to available weather data, North Dakota had 14 d >30 °C (NDSU 2024), whereas Washington had only 6 d >30 °C (WSU 2024). High nighttime temperatures can have similar effects, with night temperatures >12 °C decreasing overall plant growth (Burke 1990; Wang and Camp 2000). North Dakota had 66 nights >12 °C, whereas Washington only had 30 nights >12 °C (NDSU 2024; WSU 2024). Despite these differences in air temperatures, soil temperatures were similar between locations and were, on average, 20 to 25 °C (Table 3). Similarly, soil moisture was kept at an average of 0.29 m^3/m^3 in both North Dakota and Washington (Table 4).

The late planting time in addition to flower removal at the onset of flowering also likely contributed to reduced and delayed yields in North Dakota. An infestation of Lygus bug (*Lygus* spp.) was detrimental to one harvest in Washington but overall was a minimal contributor to diminished yields and was not treatment specific. This infestation was controlled through the application of pyrethrins at label rates (PyGanic® 5.0 EC, MGK, Minneapolis, MN, USA). North Dakota also had an outbreak of Lygus bug, with a substantial portion of malformed fruit being culled. There was a noteworthy but nonsignificant trend for marketable yield to be greater for the HM 6% psyllium and HM 6% guar gum tackifier treatments in Washington and North Dakota, respectively (Table 1). This may be due to these treatments having improved weed suppression compared with other hydromulch treatments, as reported in Ahmad et al. (2024). Improved weed suppression is positively associated with a higher percentage of tackifier, creating hydromulch with better physical properties when compared with the 2% and no tackifier treatments (Ahmad et al. 2024; Durado et al. 2024). Interestingly, yields trended to be lowest in the PE mulch control treatment. It is possible the black PE retained more heat and contributed to heat stress, manifesting in slightly lower yield (Amare and Desta 2021). This can be supported by the soil temperature data, whereby soils under PE mulch were, on average 1.2 °C warmer than all hydromulch formulations, excluding Washington's 6% guar gum treatment being slightly warmer than the PE treatment (Table 3). This was especially true in North Dakota, which had a warm growing season, potentially contributing to three of the four PE-treated plots having no marketable fruit (Table 1).

Fruit quality. No treatment effects on fruit quality were observed whereas there was an effect on juice pH and TA due to trial location (Table 1). These location effects are attributed to differences in growing and harvesting conditions between locations but could also be due to differences in how these variables were measured despite the same protocol being used. Fruit acidity as measured as pH and TA was notably higher in Washington compared with previous seasons in the same location (DeVetter et al. 2017). Again, this variation in fruit acidity is likely due to seasonal differences between growing years and are still within expected ranges. Note that no interaction effect could be enumerated due to the lack of statistically meaningful nonparametric two-way analysis.

Tissue nutrient analysis. Leaf tissue nutrient results are presented by location given the significant variation between locations especially for P, K, Mg, S, Fe, Mn, and Zn. However, no interactions existed between location and treatment except for Na (Table 5). Treatment effects were only observed for the

Table 3. Average monthly soil temperatures under hydromulch (HM) treatments applied before planting 'Albion' day-neutral strawberry in northwest Washington and North Dakota, USA, 2022. Data were collected from sensors installed at 10- and 15-cm deep in Washington and North Dakota, respectively from 15 Jun to 17 Oct 2022.

	Soil temp (°C)				
Treatment[i]	June	July	August	September	October
Washington					
HM, 2% psyllium husk	21.0	23.7	22.4	18.3	13.3
HM, 6% psyllium husk	21.4	24.1	22.6	18.4	13.5
HM, 2% guar gum	21.6	24.6	22.7	18.2	13.4
HM, 6% guar gum	23.0	26.3	23.9	18.9	13.7
HM, no tackifier	20.5	23.3	22.0	18.1	13.2
Polyethylene (control)	21.6	24.6	23.2	18.8	13.5
North Dakota					
HM, 2% psyllium husk	20.5	23.3	22.0	18.1	13.2
HM, 6% psyllium husk	21.0	23.7	22.4	18.3	13.3
HM, 2% guar gum	21.4	24.1	22.6	18.4	13.5
HM, 6% guar gum	21.6	24.6	22.7	18.2	13.4
HM, no tackifier	21.6	24.6	23.2	18.8	13.5
Polyethylene (control)	23.0	26.3	23.9	18.9	13.7

[i] Treatments include hydromulch formulations made with 2 or 6% psyllium or guar gum tackifier, no tackifier, and a polyethylene mulch control.

Table 4. Average monthly soil volumetric water content under various hydromulch (HM) treatments applied to 'Albion' day-neutral strawberry grown in northwest Washington and North Dakota, 2022. Data were collected from sensors installed at a depth of 10 cm in Washington and 15 cm in North Dakota from 15 Jun to 17 Oct 2022. The North Dakota sensors were installed at 15 cm instead of 10 cm due to a lack of soil aggregation, which caused the sidewalls of the 10-cm holes to collapse above the sensor, which could negatively affect readings.

	Soil water content (m^3/m^3)				
Treatment[i]	June	July	August	September	October
Washington					
HM, 2% psyllium husk	0.27	0.27	0.25	0.24	0.25
HM, 6% psyllium husk	0.30	0.33	0.30	0.30	0.31
HM, 2% guar gum	0.31	0.35	0.32	0.31	0.30
HM, 6% guar gum	0.28	0.31	0.28	0.27	0.27
HM, no tackifier	0.28	0.31	0.31	0.32	0.36
Polyethylene (control)	0.31	0.32	ND[ii]	ND[ii]	ND[ii]
North Dakota					
HM, 2% psyllium husk	0.29	0.29	0.30	0.28	0.26
HM, 6% psyllium husk	0.30	0.29	0.29	0.28	0.26
HM, 2% guar gum	0.31	0.30	0.30	0.30	0.28
HM, 6% guar gum	0.30	0.28	0.29	0.28	0.26
HM, no tackifier	0.30	0.29	0.30	0.30	0.30
Polyethylene (control)	0.30	0.30	0.31	0.31	0.29

[i] Treatments include hydromulch formulations made with 2 or 6% psyllium or guar gum tackifier, no tackifier, and a polyethylene mulch control.

[ii] ND denotes no data due to logger malfunction.

Table 5. Leaf tissue nutrient concentrations for 'Albion' day-neutral strawberry grown with various hydromulch (HM) treatments in Washington and North Dakota, 2022.

	Leaf tissue nutrients												
	N	P	K	Mg	Ca	S	B	Fe	Mn	Cu[ii]	Zn[ii]	Al	Na[iii]
Treatment[i]	(%)						(ppm)						
Washington													
HM, 2% psyllium husk	2.14	0.28	1.68	0.25	0.99	0.12	31.10	130.02	43.08	6.53	18.45	130.60	25.88
HM, 6% psyllium husk	2.27	0.28	1.80	0.28	1.12	0.13	34.05	152.05	42.28	6.50	18.13	171.40	34.43
HM, 2% guar gum	2.23	0.24	1.70	0.31	1.34	0.13	35.98	192.01	44.63	4.75	16.00	193.00	57.15
HM, 6% guar gum	2.19	0.26	1.75	0.27	1.13	0.12	32.30	201.00	38.90	4.95	16.18	177.93	36.45
HM, no tackifier	2.17	0.27	1.76	0.29	1.29	0.13	34.45	182.03	46.78	5.03	16.50	227.50	40.58
Polyethylene (control)	1.96	0.25	1.82	0.25	1.08	0.12	32.98	230.05	40.13	6.90	15.95	106.75	21.43
North Dakota													
HM, 2% psyllium husk	2.03	0.31	1.95	0.41	1.07	0.14	32.30	232.75	149.25	5.50	14.13	223.00	28.78
HM, 6% psyllium husk	2.02	0.33	1.92	0.39	1.00	0.13	32.10	188.25	142.00	6.13	14.88	170.00	46.25
HM, 2% guar gum	2.17	0.30	1.79	0.39	1.01	0.14	31.00	292.25	138.50	5.50	14.50	270.75	26.48
HM, 6% guar gum	2.13	0.30	1.89	0.42	1.13	0.14	34.83	204.25	134.00	5.65	12.13	184.50	23.43
HM, no tackifier	1.93	0.31	1.94	0.41	1.06	0.13	31.28	216.00	120.73	5.25	13.55	200.50	24.18
Polyethylene (control)	2.02	0.32	1.95	0.39	1.03	0.14	33.33	195.50	137.75	5.65	14.35	193.00	28.23
Significance													
Treatment	0.288	0.338	0.228	0.249	0.231	0.808	0.536	0.136	0.790	0.019	0.038	0.058	0.088
Location	0.423	<0.001	<0.001	<0.001	0.629	0.001	0.816	0.049	<0.001	0.701	<0.001	0.114	0.089
Location × treatment	0.271	0.914	0.704	0.748	0.941	0.275	0.731	0.483	0.320	0.089	0.342	0.391	0.049

[i] Treatments include hydromulch formulations made with 2% or 6% psyllium or guar gum tackifier, no tackifier, and a polyethylene mulch control.

[ii] Based on the *F*-test, a marginal significance was present. However, a lack of statistical power inhibits our ability to precisely determine these differences.

[iii] Data were analyzed across locations and separated at $P < 0.05$ using Tukey's honestly significant difference except for Na due to a marginally significant location × treatment interaction.

micronutrients Cu and Zn (both $P < 0.05$). Yet due to a lack of statistical power, further pairwise comparisons revealed no treatment effects.

Cu is an important micronutrient in strawberries as it functions as a cofactor for many enzymes, plays a vital role in respiration and photosynthetic metabolism, and may be responsible for reducing susceptibility to fungal and bacterial diseases (Osvalde et al. 2023; Sabahat et al. 2022). In Washington, only the HM 2% guar gum treatment fell inside the regional sufficiency range while all other treatments fell outside the sufficiency range of 2.6 to 4.9 ppm (Dixon et al. 2023). Leaf tissue Cu in Washington trended toward being greatest in treatments where psyllium husk was used as the tackifier and for the PE mulch control, and lowest in treatments containing guar gum. This trend is likely random as similar patterns for leaf tissue Cu in North Dakota were not observed. Furthermore, no visual symptoms of Cu toxicity were observed in the field indicating greater tolerance to elevated leaf Cu and/or leaf tissue sufficiency standards may need to be updated for the Pacific Northwest region. Comparisons to regional sufficiency standards for North Dakota were not made because no nutrient sufficiency guide for day-neutral strawberries exists for the region at the time of this publication.

Like Cu, Zn is also an important micronutrient for strawberry production, as it is the second most abundant metal in biological tissues after Fe (Lopez-Herrera et al. 2018). This is due to Zn being critical to protein and indole-3-acetic acid synthesis, membrane integrity, carbohydrate metabolism, detoxification of superoxide radicals, and is the only metal found in every enzyme type (Broadley et al. 2012). Contrary to Cu, Zn was within the sufficiency range of 11 to 20 ppm for all treatments in Washington (Dixon et al. 2023). Zn appeared to be greatest for HM 2% and 6% psyllium treatments in Washington at 18.45 ppm and 18.13 ppm, respectively, and all other measurements ranged between 15.95 ppm and 16.50 ppm. In North Dakota, the HM 6% guar gum treatment had the lowest leaf tissue Zn at 12.13 ppm. All other treatments were between 13.55 ppm to 14.88 ppm, and no discernable trends associated with hydromulch treatments were observed.

Many macronutrients were outside their sufficiency ranges in Washington, including N, P, K, Mg, and Ca. The sufficiency guide states that N should be between 2.4% to 3.0% (Dixon et al. 2023). However, all treatments in Washington were below 2.4%, with the lowest being the PE mulch control at 1.96%. The remaining treatments ranged between 2.14% to 2.33%. Nitrogen status may have impacted crop performance and led to lower yields. Similarly, P was just outside the 0.3% to 0.4% sufficiency range, with HM 2% guar gum numerically the lowest at 0.24% (Dixon et al. 2023). Potassium was nearly within its sufficiency range of 1.3% to 1.8%, with just the PE treatment being above at 1.82%. Magnesium was also mostly within sufficiency ranges. Leaf Ca concentrations were mostly within their sufficiency range of 1.0% to 2.2%, except for HM 2% psyllium husk, which was close to threshold values at 0.99%. Similar to the discussion on Cu, regional guidelines for sufficiency ranges may need to be updated for Washington as they are largely based on findings outside of Washington. No leaf tissue sufficiency guide exists for day-neutral strawberries grown in North Dakota and the surrounding region.

After accounting for the treatment effects for Cu and Zn, which were not impacted by hydromulching, and considering the findings from Washington, hydromulch treatments did not influence leaf tissue nutrient concentrations. However, Simard et al. (1998) showed that applications at or below 12 t of dry matter per ha of low nutrient paper sludge increased soil Melich-3 extractable P and K, and applications of 18 t of dry matter per ha created short term N immobilization despite the addition of N fertilizer to paper sludge (Camberato et al. 2006; Norrie and Gosselin 1996). Immobilization may have been caused by the degradation of labile or fixed carbon on soil colloids, and nitrogen sampling the following spring proved this immobilization temporary due to inorganic N being significantly higher in plots where more sludge was applied (Simard et al. 1998). While temporary immobilization is possible with hydromulch applications, the rate Simard et al. (1998) used to achieve significant immobilization was 13.5 t of dry matter per ha greater than what was used in the current experiment.

Conclusions

Hydromulches maintained strawberry yield and fruit quality within two contrasting environments in this study. Overall, low yields observed in North Dakota may have been ameliorated through alternative planting dates or a different production system, such as fall planting. Although many nutrients were outside their sufficiency ranges in Washington, this occurrence was not treatment-specific and was observed in the PE mulch control as well. Therefore, our results indicate that hydromulch did not contribute to abnormal nutrient status, but this may be different if hydromulches are incorporated into the soil due to immobilization. These results demonstrate the commercial potential of hydromulch in horticultural systems. Further research is required to analyze the economics of this alternative mulch technology and understand the long-term soil health and nutrient dynamics of incorporating hydromulch into the soil. The focus should also be on fine-tuning feedstock acquisition and the application system so that it is scalable, affordable, and cost-effective. Research on hydromulch durability and performance in biennial or perennial strawberry cropping systems is also advised, as many strawberry growers maintain plantings for longer than 1 year.

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