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Industrial hemp yield and chemical composition as influenced by row spacing, fertilization, and environmental conditions

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Abstract

Industrial hemp (*Cannabis sativa* L.) production is expanding in the United States, generating sustained interest in this multipurpose crop, though the optimal agronomic conditions (e.g., row spacing, planting density, and nutrient management) for maximizing fiber yield remain unclear in many regions. Key factors like row spacing not only affect resource utilization but also play a crucial role in weed suppression, especially in regenerative organic systems. This research at the Rodale Institute, Kutztown, PA, examined the effects of row spacing (19 cm narrow vs. 38 cm wide) and fertilization treatments (control, blood meal containing 12% N at 112 kg ha^{-1} and 224 kg ha^{-1}, and compost at 60 t ha^{-1}) on yield and chemical composition of industrial hemp seed (cultivar: Canda) over two growing seasons (2019 and 2020). The narrow row spacing increased plant and stalk density, boosting bast fiber yield, while wider spacing promoted weed biomass due to reduced crop competition. Higher temperatures in the late growing season in 2020 led to 3.5 times increase in biomass yield and improved grain protein content. Principal component analysis indicated that compost influenced nutrient availability and heavy metal uptake more strongly than row spacing or blood meal treatments. Blood meal had limited effects, likely due to insufficient application rates, but showed promise for minimizing heavy metal uptake compared to compost. Optimal crop performance depends on the interaction between climatic conditions and agronomic practices. Selecting appropriate row spacing and nutrient sources is essential for enhancing hemp production while reducing input costs and minimizing environmental impact.

Plain Language Summary

Industrial hemp is becoming more popular in the United States, but the best way to grow it for fiber is still unclear. This study at the Rodale Institute tested how different

Abbreviations: CBD, cannabidiol; GDD, growing degree days; PCA, principal component analysis; THC, delta-9-tetrahydrocannabinol.

row spacings (narrow vs. wide) and fertilizers (compost, blood meal, or none) affect hemp growth and yield over 2 years in regenerative organic systems. Narrow rows led to more plants and higher fiber yields, while wider rows allowed more weeds to grow. The compost helped plants take in nutrients but also increased heavy metals. Blood meal had a smaller impact but seemed to reduce heavy metal uptake. The study shows that choosing the right spacing and fertilizer is key to growing healthy hemp while keeping costs and environmental impact low.

1 | INTRODUCTION

Hemp (*Cannabis sativa* L.) is a rapidly emerging, high-value specialty crop with a range of uses, including fiber, seed, and cannabidiol (CBD) production (Adesina et al., 2020; Kaiser et al., 2015; Panday et al., 2025). The industrial hemp, grown primarily for its industrial uses, is mainly cultivated for its bast fibers, which are widely utilized in the textile industries. Hemp fibers present a viable alternative to cotton, offering a 77.6% reduction in agricultural costs (Schumacher et al., 2020). These fibers are highly valued for their low density, water resistance, high specific strength, non-abrasiveness, stiffness, and biodegradability (Manaia et al., 2019; Rehman et al., 2021). The hemp stalk consists of two primary fiber components: hurd fibers, which constitute 70%–80% of the stalk and are commonly used in livestock bedding and fiberboard production, and bast fibers, comprising 20%–30% of the stalk, which are used in the automotive and paper industries (Daniels, 2019; Miller, 1991). Despite the economic and industrial potential of hemp, agronomic knowledge, fertilization guidelines, and processing infrastructure remain underdeveloped in the United States (Adesina et al., 2020; Wylie et al., 2021).

Hemp yield and fiber quality can vary significantly depending on soil characteristics, fertilizer application rates, cultivars, planting density, and environmental factors (Vidković et al., 2023). For instances, a study in Kunming, China, by Deng et al. (2019) indicated that optimal hemp fiber yields, exceeding 2200 kg ha^{-1}, could be achieved under a planting density of 329,950–371,500 plants ha^{-1} and nitrogen (N), phosphorus (P), and potassium (K) application rates of 251–273, 85–95, and 212–238 kg ha^{-1}, respectively. In Serbia, Višković et al. (2024) studied the impact of five cultivars (Helena, J × USO31, Bob-1, H × USO31, and Marina), three seeding dates (early April, May, and June), and three inter-row spacings (12.5, 25, and 50 cm) on hemp fiber and seed yield. Results indicated that fiber content varied from 26.0% to 49.7%, with Marina having the highest fiber content. Cultivars H × USO31 and J × USO31 yielded the most seeds, whereas Marina had the lowest seed yield. The hemp seeds contained an average of 88.6% unsaturated fatty acids and 66.8% polyunsaturated fatty acids (Leonard et al., 2020).

Field studies on hemp cultivation in the United States are limited, leading to uncertainties about the best management practices for planting, crop, and nutrient management. Adesina et al. (2020) reviewed hemp agronomic practices, reporting that row spacing typically ranges from 7.6 to 17.8 cm for fiber and seed production, though some studies suggest wider spacing of 20–40 cm for fiber crops. The optimal seeding depth varies between 1.9 and 3.2 cm. Higher plant populations in fiber hemp facilitate rapid canopy closure, effectively suppressing weed competition (Adesina et al., 2020). In the Northern British Columbia, Forrest and Young (2006) examined the effects of organic and inorganic N fertilizers on fédrina cultivar, planted at a density of 90 stems m^{-2}, in greenhouse and field settings. Organic fertilizers, Alaskan fishmeal and bloodmeal, proved to be a viable alternative to inorganic N (ammonium sulphate) and P fertilizer (triple superphosphate). The application of 150–300 kg ha^{-1} of any N fertilizer types improved plant morphology, secondary phloem fiber, and xylem in the field, while 90 kg P_2O_5 ha^{-1} enhanced these traits in the greenhouse. The author also observed that the absence of N or P fertilizers promoted primary phloem fiber in both field and greenhouse settings.

In Québec, Canada, Aubin et al. (2015) found that applying 200 kg N ha^{-1} increased biomass yield from 1674 to 4209 kg ha^{-1} and seed yield from 519 to 1340 kg ha^{-1} compared to the unfertilized control. Rahemi et al. (2021) found that industrial hemp cultivar Carmagnola produced higher biomass yields and showed potential for adoption as a local fiber cultivar in the mid-Atlantic region. In Wisconsin, Ortmeier-Clarke et al. (2023) examined the impact of two hemp cultivars (X-59 and CRS-1), three seeding rates (22, 34, and 45 kg ha^{-1}), and three N levels (0, 67, and 134 kg ha^{-1}) on hemp yield. At the Arlington site, any N levels had no effect on fiber yield, but there was an interaction between cultivar, seeding rate, and N level that influenced grain yield. At the Chippewa Falls site in Wisconsin, fiber yield increased by 20% and grain yield by 52% when the N rate was raised from 0 to 67 or 134 kg ha^{-1}. These results highlight the variability in seeding rates and nutrient requirements across various locations, underscoring the need for site-specific agronomic recommendations.

Given the growing interest in fiber hemp, there is an urgent need to develop agronomic practices that are specifically adapted to the local soil and climates. Therefore, this research aimed to evaluate the impact of row spacing and fertilization on the yield and chemical composition of industrial hemp in the northeastern region, providing key insights for growers while reducing input costs and minimizing environmental impact.

Core Ideas

- The narrow row spacing (19 cm) increased plant density, leading to higher bast fiber yield compared to 38 cm spacing in hemp.
- The compost improved nutrient uptake but also elevated heavy metal concentrations (e.g., Pb) in plant and grain tissues.
- The blood meal enhanced fiber and hurd yields, showing an inverse relationship with heavy metals and positive link to plant carbon.
- The optimal crop performance depends on the interaction between climatic conditions and agronomic practices.

2 | MATERIALS AND METHODS

2.1 | Site description

Field studies were conducted from June to September in 2019 and 2020 at the Rodale Institute Organic Research Farm in Kutztown, PA, using different fields each year. The research site consists of Clarksburg silt loam soil (fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalf) with slope from 3% to 5%. To establish baseline soil conditions, chemical properties were assessed at a depth of 0–20 cm each year. Soil samples were collected from multiple points and values were averaged across the sites to account for natural variability and enhance data representation. The soil pH remained consistent at 6.7 across both study years. Averaged across the sites, total carbon (C) and N were 2.86% and 0.31%, and 2.96% and 0.34% in 2019 and 2020, respectively. Further details about soil analysis are presented in Table 1, while the methods used for nutrient testing are described in Panday et al. (2025).

The region is characterized by continental climate with significant annual variation in temperature. Daily maximum and minimum air temperature, precipitation, long-term air temperature, and average long-term precipitation data were obtained from the Reading Municipal Airport, Reading, PA (Figure 1). The average daily minimum temperatures drop below freezing during December to March, and average daily maximum temperatures exceed 30°C during July to August.

The average monthly temperature during the growing season (June to September) remained consistent from year to year, as shown in Figure 1. However, daily temperature monitoring revealed that early season temperatures (June and July) were higher in 2019 than in 2020, whereas late season temperatures (August and September) were warmer in 2020 than in 2019 (data not shown). The optimal temperature ranges vary with hemp growth stages: germination and seedling (8–10°C), vegetative (21–29°C), and flowering (18–27°C). Thus, the observed average temperatures align with hemp's preferred range, supporting healthy development. The cumulative rainfall was comparable between the years, with 562 mm in 2019 and 618 mm in 2020. Similarly, the accumulated growing degree days (GDD) with a base temperature of 10°C from June to August were 2122 and 2236 in 2019 and 2020, respectively.

TABLE 1 Soil characteristics of 0 to 20 cm depth at research sites in 2019 and 2020 in Kutztown, PA.

Soil property	2019	2020
pH	6.7	6.7
Organic matter (OM, %)	4.57	5.01
Total carbon (C, %)	2.86	2.96
Total nitrogen (N, %)	0.31	0.34
Phosphorus (P, mg kg^{-1})	295.36	14.82
Potassium (K, mg kg^{-1})	119.17	68.93
Calcium (Ca, mg kg^{-1})	2400.67	1218.31
Magnesium (Mg, mg kg^{-1})	228.57	84.48
Sulfur (S, mg kg^{-1})	17.66	3.03
Zinc (Zn, mg kg^{-1})	9.33	0.27
Manganese (Mn, mg kg^{-1})	209.62	7.26
Copper (Cu, mg kg^{-1})	13.09	0.10
Iron (Fe, mg kg^{-1})	233.24	0.41
Aluminum (Al, mg kg^{-1})	162.00	7.92

2.2 | Experimental layout

The experiment was arranged in split-plot design, with two crop row spacings (19 and 38 cm) as the main plots and four fertilizer treatments as subplots, each replicated three times. The fertilizer treatments were no fertilizer (control), blood meal at 112 kg ha^{-1} (BM112), blood meal at 224 kg ha^{-1} (BM224), and compost at 60 t ha^{-1} on fresh weight basis (compost). Each plot measured 3 m × 12 m. Nitrogen was provided using blood meal, an Organic Material Review Institute–listed, cost-effective organic fertilizer produced from dried animal blood, containing 12% N but lacking P and K (Panday, Bhusal, et al., 2024). The compost was prepared on-site, cured for 1 year, and contained 2.6% total N

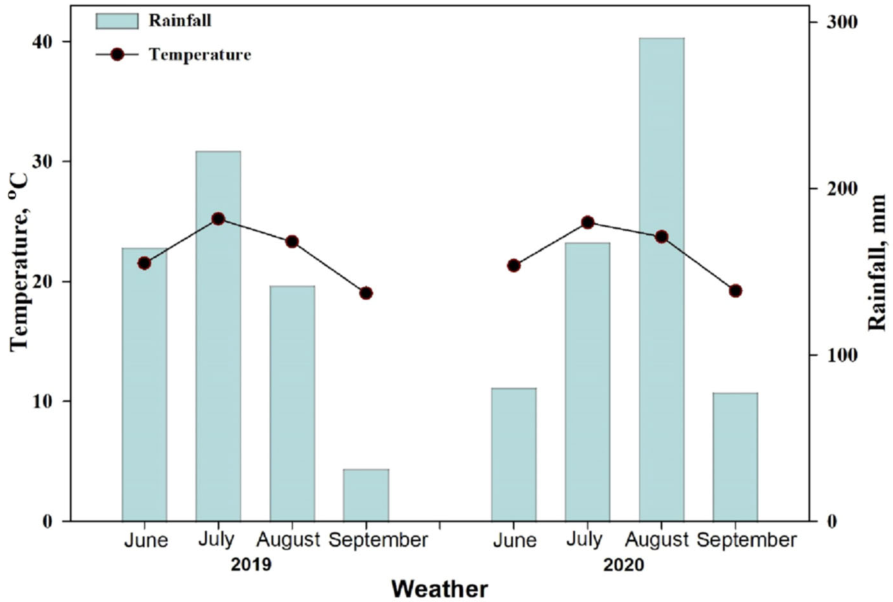

FIGURE 1 Mean temperature and cumulative rainfall during the growing season at research site in 2019 and 2020.

and applied at a rate commonly practiced by many farmers. In 2020, one of the treatments included a fertilizer application rate of 168 kg ha^{-1} using Fertrell (NPK 7:0:1). However, this treatment is not reported in the manuscript to maintain consistency with the treatment applied in both years of study.

The hemp was preceded by barley (*Hordeum vulgare* L.) in 2019 and cereal rye (*Secale cereale* L.) in 2020 to equilibrate the nutrient status of the soil. The field was moldboard plowed once and disked as needed between April and May each year. The compost and blood meal fertilizers were incorporated with a packer just before planting. The Canda hemp cultivar from Canada was sown in early June by using a grain drill at a rate of 39.2 kg ha^{-1} in 19 cm spacing and 19.6 kg ha^{-1} in 38 cm spacing. This cultivar is grown for fiber and grain production and has a medium growing cycle of 100–120 days (Figure 2). The seeding rate was adjusted after accounting for germination rates and mortality rates of 30%. In both years, seeds were planted in early June and harvested in early September using a sickle bar mower.

2.3 | Data collection

Seedling density was determined by counting plants in a 0.75 m × 0.75 m quadrant in each plot. The plant height and stalk density were measured prior to the harvest. Weeds were collected within 0.56 m^2 area, dried at 43°C to a constant weight to determine dry biomass. Whole plant biomass samples were taken right before harvest, dried, ground, and sent to the Cornell Nutrient Analysis Lab to analyze total C and N, as well as dry ash nutrients (P, K, Ca, Mg, S, B, Fe, Mn, Zn, Cu, Mo, Al, Cd, Pb, and Cr) in tissue. Fifteen days before

FIGURE 2 Fiber hemp at 19 cm spacing in the research field.

physiological maturity, hemp plants were tested for delta-9-tetrahydrocannabinol (THC) content. Although this testing was not required after obtaining a permit to grow fiber hemp in

Pennsylvania, we conducted it to ensure THC levels remained below the permissible limit of 0.3% for both years.

Seeds were harvested in late August to early September at physiological maturity (25% moisture content), when 70%–80% male plants were in flowering stage. The total wet biomass was measured by collecting all plants in two 0.75 m × 0.75 m quadrants in each plot. Bast fiber and hurd weights were estimated at 20% (±2) and 70% (±3) of the total biomass weight, respectively, based on the reference data from a separate trial conducted at the Rodale Institute. To prepare hemp stalks for retting, the inflorescence and axillary branches were removed before weighing the wet stalks. A subsample of 10 stalks was collected for field (dew) retting and left in the field for 3 weeks until the bast fiber (bark material) naturally separates from the woody core or hurd. After retting, bast fiber and hurd were oven dried separately to determine their dry weight. Grains were separated from harvested buds and weighed. Grain samples were sent to the Penn State Nutrient Analysis Lab, University Park, PA, for nutrient quality analysis. This included determining grain crude protein using the Kjeldahl method, crude fiber through acid–base digestion, and crude fat using ether extraction.

2.4 | Statistical analysis

The statistical analysis was performed using the R statistical software version 4.3.3. An analysis of variance was conducted to assess the main effects of row spacing, fertilization, year, and their interactions, with replication treated as random effect using the "sp.plot()" function. The Post hoc analysis for mean separation was performed using the least significant difference test (via "LSD.test()" function) at a significance level $\alpha = 0.05$. To reduce data dimensionality and explore potential correlations among the observed parameters in this research, principal component analysis (PCA) was applied to a dataset of row spacing and fertilizer treatments for grain and plant nutrients. The "autoplot()" function from the ggfortify package in R was used to visualize PCA results, while the "ggplot2" package was employed for data visualization.

3 | RESULTS AND DISCUSSION

3.1 | Plant density, yield, and fiber weight

The hemp seedling density ranged from 16 to 85 plants m^{-2}. This density was significantly affected by the year × row spacing and row spacing × fertilizer interactions (Table 2). The seedling density was maximum at 19 cm spacing for both years (Figure 3a), this difference was expected, with more plants established at 19 cm spacing than at 38 cm. Likewise, averaged across fertilizer treatments, the seedling density was greater at narrow row spacing than at wide spacing (Figure 3b). Additionally, there was a significant interaction between row spacing and fertilizer for stalk density, which was shown by more stalk density at a 19 cm row spacing than at 38 cm, regardless of the fertilizer treatments (Figure 3c). These observations suggest that fiber hemp performs well in high density to encourage stalk growth, a finding consistence with Amaducci et al. (2008), who reported comparable results in a 4-year study into the effect of plant density on the morphology and production of fiber hemp in Italy. However, it is important to note that the increased stalk density is indirectly associated with a stem diameter, which is often associated with higher bast fiber yield. In the current study, plants grown at higher densities (19 cm spacing) developed thinner stems, which promoted a higher proportion of bast fiber due to reduced lignification (Struik et al., 2000). This highlights a trade-off between plant density and fiber quality, where narrower spacing may enhance bast fiber yield, it may also affect stalk robustness and processing efficiency.

While plant height showed no significant differences between treatments, the 2020 growing season produced superior crop performance, particularly in fields with reduced weed pressure and taller plant stature. The environmental conditions in 2020 included higher late-season temperatures, better soil moisture during peak growth, and increased GDD, which contributed to extended vegetative and maturation periods for hemp. This extension is crucial as it allows for longer biomass accumulation which is directly beneficial for both fiber yield and quality (Gill et al., 2023). This aligns with research suggesting that optimal soil moisture is critical for ensuring efficient nutrient transfer from soil to plant, which is vital for uniform and robust stand establishment (Cosentino et al., 2013; Dudziec et al., 2024; Visković et al., 2024). Likewise, higher GDD indicates more accumulated heat units and correlates with accelerated growth rates and enhanced physiological activities, which are beneficial for both growth and fiber production (Rahemi et al., 2021).

The hemp biomass yield exhibited significant variation between 2019 and 2020 (Table 2), potentially due to environmental factors and inherent soil fertility. Biomass yields in 2020 were almost 3.5 times greater, ranging from 476 to 6147 kg ha^{-1}, compared to 2019. The average yield in 2020 was (3349 kg ha^{-1}), surpassing reported yields in Manhattan, KS (2832 kg ha^{-1}), and Alberta, Canada (1401 kg ha^{-1}), for the same cultivar (Griffin et al., 2021; NPARA, 2022). The weed biomass yield was affected by spacing and year, as well as interaction between row spacing and fertilizer treatments. The weed biomass was greater in 2019 (Table 2) and across all fertilizer treatments at 38 cm row spacing (Figure 3d). These results suggest that wider row spacing can create more favorable conditions for weed growth, which is due to reduced crop–weed competition, and aligns with previous findings that emphasized the role of crop density in weed suppression (Kristensen et al., 2008; Hall et al., 2014),

TABLE 2 Effects of row spacing, fertilizer, and studied year on observed parameters of fiber hemp production in the northeastern region.

Source of variation	Seedling density (plant m^{-2})	Stalk density (stalk m^{-2})	Plant height (cm)	Hemp biomass (kg ha^{-1})	Weed biomass (kg ha^{-1})	Bast fiber weight (kg ha^{-1})	Hurd weight (kg ha^{-1})	Grain weight (kg ha^{-1})	Grain crude protein (%)	Grain crude fiber (%)	Grain crude fat (%)	Plant total C (g kg^{-1})	Plant total N (g kg^{-1})
Spacing (cm)													
19	53.95	29.11	121.44	2520.88	180.96b	487.50	1706.24	627.33	22.06	33.26	28.45	425.31	10.47
38	28.48	16.53	120.62	1790.04	317.83a	327.53	1146.37	434.88	22.05	33.29	28.64	429.75	11.20
Significance	**	**	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS
Fertilizer													
Control	43.99	23.63	117.89	1937.17	222.74	362.35	1268.22	495.25	21.88	33.13	29.11	424.18	11.41
BM112	38.92	22.31	121.23	2369.67	252.89	454.35	1590.22	598.83	21.18	33.31	27.87	432.70	10.65
BM224	38.42	21.19	120.59	2167.00	260.83	409.31	1432.59	527.92	21.90	33.28	28.55	425.98	10.89
Compost	43.55	24.14	124.41	2148.00	261.11	404.05	1414.19	502.42	23.27	33.38	28.66	427.26	10.37
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year													
2019	33.60	18.66b	119.30	961.67b	313.46a	152.45b	599.62b	135.63b	21.16b	33.28	29.35a	405.21b	9.85b
2020	48.83	26.97a	122.77	3349.25a	185.33b	669.85a	2344.47a	926.58a	22.95a	33.27	27.75b	449.85a	11.81a
Significance	*	**	NS	**	*	**	**	**	*	NS	**	**	*
Interaction													
Year × spacing	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year × fertilizer	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Spacing × fertilizer	***	**	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS

Note: Fertilizer treatment includes four levels: no fertilizer (control), blood meal at 112 kg ha^{-1} (BM112), blood meal at 224 kg ha^{-1} (BM224), and compost at 60 t ha^{-1} (compost). Means in a column followed by same lowercase letter are not significantly different. When the interaction effect was significant, the main effect was not reported. The three-way interaction was not reported due to absence of any significant observed parameters.

Abbreviation: NS, not significant.

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

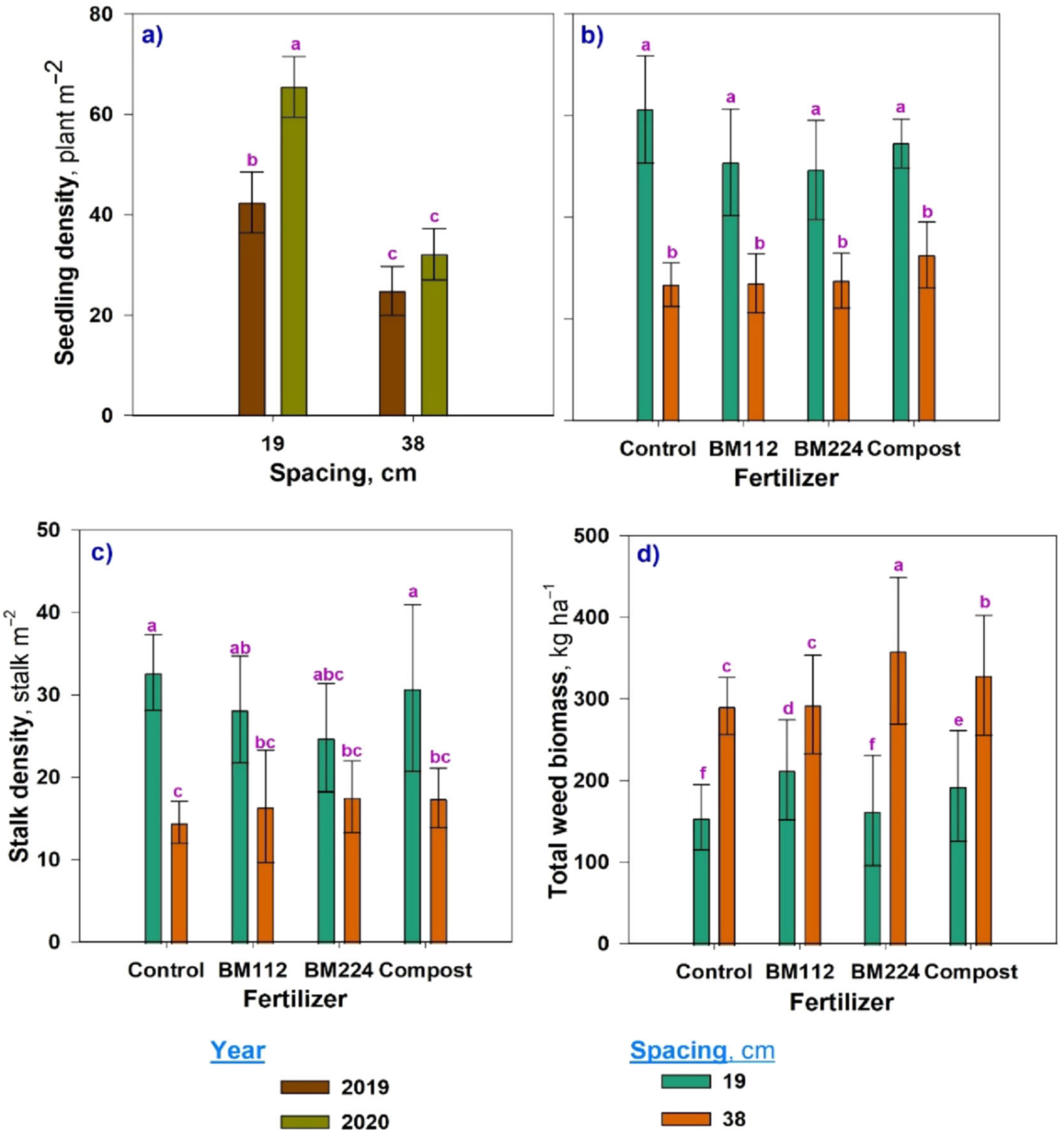

FIGURE 3 Interaction effects of row spacing, fertilizer, or year on observed parameters of fiber hemp: (a) spacing and year on seedling density, (b) spacing and fertilizer on seedling density, (c) spacing and fertilizer on stalk density, and (d) spacing and fertilizer on weed biomass. Fertilizer treatment includes four levels: no fertilizer (control), blood meal at 112 kg ha^{-1} (BM112), blood meal at 224 kg ha^{-1} (BM224), and compost at 60 t ha^{-1} (compost). Means (±SE) with different lowercase letters are significantly different at $p < 0.05$.

with lower plant populations (100 plants m^{-2}) leading to significantly higher weed biomass than higher densities (200, 300, or 400 plants m^{-2}).

The bast fiber, hurd, and grain weight of fiber hemp were significantly influenced by the year but remained unaffected by row spacing and fertilizer treatments (Table 2). This observation underscores the predominance of environmental conditions, including factors such as temperature, rainfall, and year-to-year variability likely played a more critical role in determining fiber and grain yields. Such environmental influences have been well documented in earlier studies for a significant impact of annual climatic variability on fiber quality and yield in hemp (Amaducci et al., 2008; Hammami et al., 2022).

The lack of significant fertilization effects on observed parameters such as biomass yield, bast fiber, hurd, and grain weight suggests that the application rates of blood meal, which is a main fertilizer in the current research, were applied at much lower rates (i.e., around 13.5 and 27 kg N ha^{-1}) or may have been insufficient to show a strong response. This occurred due to the lack of established guidelines for the hemp fertilization. At the same time, this cautious approach was taken to prevent potential negative consequences associated with excessive N application, such as environmental pollution and diminished crop quality.

Notably, the hemp crop performance was better in 2020 despite lower soil nutrient concentrations compared to 2019,

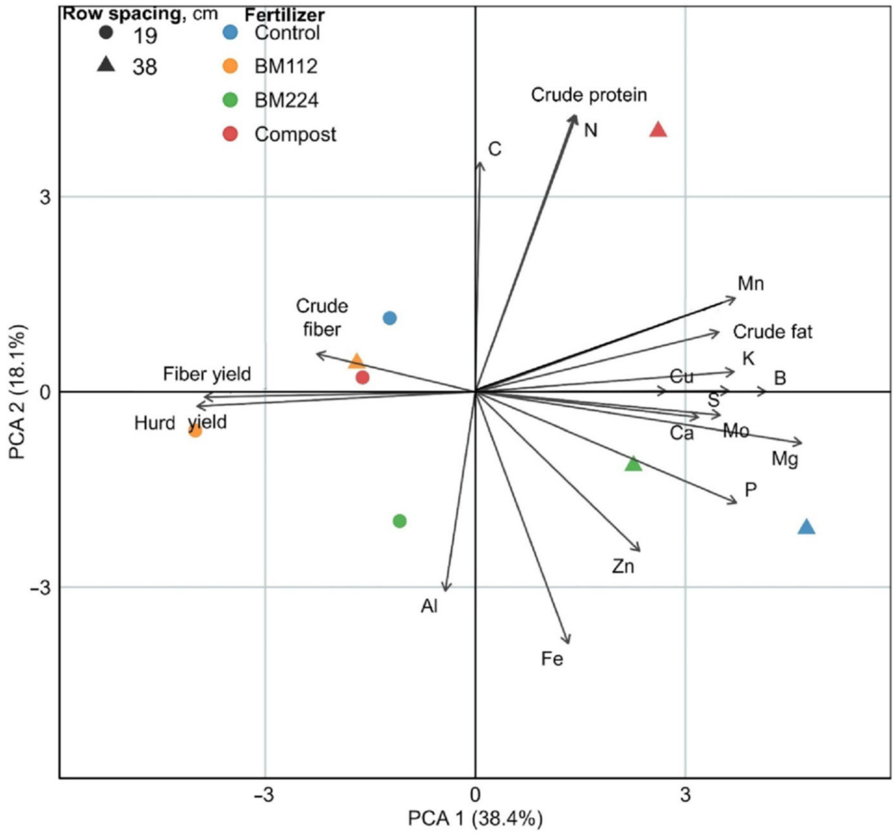

FIGURE 4 Principal component analysis (PCA) biplot depicting the relationship between measured grain nutrient variables and fiber hemp yield (bast fiber and hurd yield). PC1 on *X*-axis accounted for 38.4% of the total variability, which PC2 explained 18.1% of total variability and is shown on the *Y*-axis. Fertilizer treatment includes four levels: no fertilizer (control), blood meal at 112 kg ha^{-1} (BM112), blood meal at 224 kg ha^{-1} (BM224), and compost at 60 t ha^{-1} (compost).

except for N concentration (Table 1). This suggests that the inherent soil fertility in 2019 may have been adequate to support crop nutrient needs, reducing the observable effects of additional fertilizer inputs. However, even with declining nutrient levels in 2020, fertilizer treatments did not lead to significant improvements in main yield-related parameters, reinforcing the dominance of climatic factors over nutrient availability in influencing plant performance.

Although site-specific fertilizer recommendations for hemp in Pennsylvania are currently lacking, the Agricultural Analytical Services Laboratory at Penn State has provided guidelines for hemp seed production, recommending 68 kg of N, 13.6 kg of P_2O_5, and 9.1 kg of K_2O for optimal yields on soils with sufficient P and K (AASL, 2018). Recent studies have indicated that hemp's response to N can vary significantly based on environmental conditions and specific cultivation practices. For instance, research in the northeastern United States suggests that optimal N rates for CBD hemp production range between 168 and 224 kg N ha^{-1}, with banding methods proving more effective than broadcasting (Panday et al., 2025). Given the variability in environmental conditions, there remains a need for adaptive management strategies to optimize row spacing and fertilizer application while improving weed control and overall crop performance (Dhakal et al., 2024; Panday, Afshar, et al., 2024; Struik et al., 2000).

3.2 | Grain and plant nutrients

The analysis of hemp grain and plant nutrients revealed notable annual variations in crude protein and crude fat concentrations, as well as in plant total C and N between the years 2019 and 2020; however, it remained unchanged for row spacing and fertilizer treatments (Table 2). The crude protein content in hemp grain ranged from 17.4% to 25.6% (at moisture range of 4.3%–5.8%), with a significant increase in 2020, compared to 2019.

Similar findings were reported by Rahemi et al. (2021) and Lan et al. (2019), who observed a 24.5%–26.2% crude protein at a moisture range of 4.5%–5.0% in Canda cultivar. Their studies also indicated that the crop year influenced nutritional mineral content. Callaway (2004) and Lančaričová et al. (2021) reported approximately 24.8% crude protein in Finola hemp cultivar and noted that hemp protein content

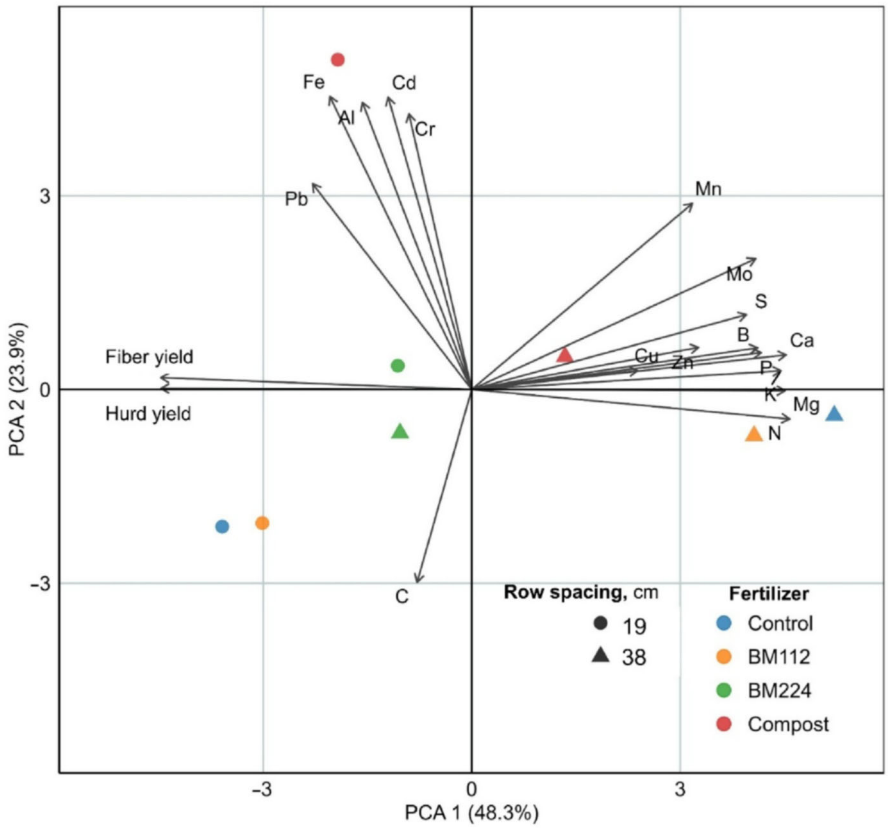

FIGURE 5 Principal component analysis (PCA) biplot depicting the relationship between measured plant nutrient variables and fiber hemp yield (bast fiber and hurd yield). PC1 on *X*-axis accounted 48.3% of the total variability, which PC2 explained 23.9% of total variability and is shown on the *Y*-axis. Fertilizer treatment includes four levels: no fertilizer (control), blood meal at 112 kg ha^{-1} (BM112), blood meal at 224 kg ha^{-1} (BM224), and compost at 60 t ha^{-1} (compost).

can vary based on growing conditions and genetic factors. Comparatively higher temperatures in 2020 enhanced protein synthesis, as warmer temperatures are known to improve protein accumulation in crops (Köhler et al., 2019). Additionally, climatic conditions associated with harvest time can influence the seed ripeness and overall quality.

Conversely, the greater crude fat observed in 2019, ranging from 30.9% to 36.1% (Table 2), suggests that cooler temperatures or other environmental factors may have favored lipid accumulation, consistent with research indicating that fat content in seeds can be influenced by temperature and stress conditions during seed filling (Kumar et al., 2023; Sehgal et al., 2018). Despite the variation in crude protein and crude fat, the crude fiber content remained consistent across years, ranging from 26.0% to 31.0% (Table 2), which suggests that fiber levels are less responsive to annual climatic changes. This is supported by similar studies reporting that the genetic makeup of hemp plays a more dominant role in determining fiber contents (Petit et al., 2020; Struik et al., 2000).

Both total C and N in the plant biomass were significantly higher in 2020 compared to 2019 (Table 2). This increase reflects enhanced plant growth conditions, such as improved soil fertility (with higher organic matter and N in 2020; Table 1) and more favorable weather patterns, which facilitated greater nutrient uptake and biomass accumulation (Pregitzer & King, 2005). This aligns with findings that optimal conditions can lead to increased C and N concentrations in plant tissues (Fontaine et al., 2024; Yang et al., 2021). However, higher C could also indicate a greater proportion of structural compounds rather than increased metabolic activity, while higher N may suggest luxury consumption without necessarily benefiting plant health. These nuances highlight the need for careful interpretation of these elevated C and N concentrations, as they do not always directly correlate with improved productivity or vigor (Tripler et al., 2002).

The observed variations in hemp grain composition and plant nutrients between 2019 and 2020 are further explained by the PCA results. While row spacing, especially wider spacing (38 cm), influenced certain nutrient concentrations and yield parameters, its impact was less pronounced compared to fertilizer type (Figures 4 and 5). The compost treatment exhibited a strong association with crude protein and N in grain nutrient composition, indicating enhanced protein content (Figure 4). However, compost was also consistently associated with higher concentrations of heavy metals (e.g., Pb, Al, Fe, Cd, and Cr), indicating a potential risk of metal accumulation in both plant and grain tissues. This finding aligns with studies reporting that compost derived from landfill sites often contains heavy metal concentrations and organic pollutants exceeding safe limits, thereby increasing the risk of plant accumulation (Kupper et al., 2014; Pawłowski, 2011). For instance, a study found that compost from landfills had levels surpassing the European Union requirements for Cd, Cu, Ni, Pb, and Zn, with plant uptake following the order Cd > Pb > Cu > Ni > Cr > Zn > Fe > Mn, thereby increasing the risks of these metals entering the food chain (Abd-Elhalim et al., 2025). Therefore, a thorough evaluation of compost quality is crucial before its agricultural use to mitigate the risks associated with heavy metal contamination.

In contrast, the BM224 treatment demonstrated a more balanced nutrient profile, clusters away from heavy metals and aligning more closely with beneficial nutrient concentrations, indicating its suitability for minimizing heavy metal uptake. Supporting this, the BM224 treatment was positively correlated with fiber and hurd yields (Figure 4). Interestingly, fiber and hurd yields were inversely correlated with heavy metals and positively associated with C, implying that higher fiber and hurd yields are linked to better C accumulation rather than metal nutrient uptake.

This suggests that blood meal may serve as a safer alternative to compost regarding heavy metal accumulation. While specific literature on the effects of blood meal at variation application rates is limited, broader studies on fertilizer-induced metal uptake highlight the significance influence of fertilizer source and composition on metal accumulation in plants. In addition, while industrial hemp is known for its phytoremediation capabilities (Testa et al., 2023; Wang et al., 2021), it is crucial to select fertilizers that do not introduce additional heavy metals into the soil. In summary, selecting an appropriate fertilizer, such as blood meal, is essential for optimizing nutrient uptake and minimizing heavy metal accumulation in industrial hemp production.

4 | CONCLUSIONS

Our study reveals the complex interactions between row spacing, fertilizer application, and environmental factors on fiber hemp production in the northeastern region. The narrow row spacing (19 cm) led to higher plant density, which promoted stalk growth and resulted in greater bast fiber yield. In contrast, the wider row spacing (38 cm) increased weed biomass due to reduced crop competition. The compost application significantly influenced nutrient availability but also contributed to higher heavy metal uptake, underscoring the need for careful nutrient source selection. While blood meal showed potential for minimizing heavy metal accumulation, its limited impact on nutrient availability suggests the need for further research at higher application rates, as this could potentially enhance nutrient availability and improve overall crop performance. Given the strong influence of climatic variability on crop performance, future studies should explore the interactive effects of agronomic practices and environmental conditions to optimize hemp production while minimizing ecological risks.

AUTHOR CONTRIBUTIONS

Dinesh Panday: Conceptualization; formal analysis; methodology; resources; software; validation; visualization; writing—original draft; writing—review and editing. **Bharat Sharma Acharya**: Validation; writing—original draft; writing—review and editing. **Madhav Dhakal**: Conceptualization; data curation; formal analysis; resources; software; validation; visualization; writing—original draft; writing—review and editing. **Tara Caton**: Funding acquisition; investigation; methodology; project administration; resources; validation; writing—review and editing. **Casey M Lapham**: Data curation; methodology; project administration; validation; writing—review and editing. **Andrew Smith**: Funding acquisition; project administration; validation; writing—review and editing. **Arash Ghalehgolabbehbahani**: Validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this research are available on request from corresponding author.

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