**Interpretive summary**

**Graphical abstract**

**Running head:**

**Survey of Management Practices, Bulk Tank Milk Bacteriology, and Udder Health and Hygiene Metrics on Organic Dairy Farms in Vermont**

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**Abstract**

A cross-sectional observational study on organic dairies had the objective of identifying whether bulk tank milk quality, udder health and hygiene outcomes were associated with facility type, and whether bedded pack systems are a viable option for winter housing in Vermont. We aimed to collect bulk tank milk samples, udder hygiene scores, and complete a survey on mastitis risk and bedding management on 40 farms, in order to compare the two most common winter housing systems in the state (freestalls, tiestalls) with those using a bedded pack. The survey was completed on 21 farms (5 bedded packs, 6 freestalls, 10 tiestalls) before interruption due to the COVID-19 pandemic. Dairy Herd Improvement Association records captured included avg. somatic cell score (SCS), standardized 150-day milk (STD 150-day milk), % cows with current high SCS (“elevSCS,” ≥4.0), % cows with newly-elevated SCS (“newSCS,” previous SCS <4.0 to current ≥4.0), and % cows with chronically-elevated SCS (“chronSCS,” ≥4.0 last two tests). There were no differences between cow-level udder health measures captured from Dairy Herd Improvement Association records, bulk tank milk somatic cell count (BTSCC), bulk tank aerobic culture data, milk production, and udder hygiene scores between facility types. A multivariable model to describe outcomes by facility type was completed, but suffered from limited statistical power due to small group sample sizes. Subsequently, we focused our analyses on univariate linear regression to identify associations between management factors and outcomes for all 21 farms combined. Farms with deeper bedding showed a tendency toward a lower BTSCC, lower newSCS, lower elevSCS, lower avg. SCS, and improved hygiene metrics. Farms with lower mean udder hygiene scores tended towards having lower chronSCS, lower elevSCS, and lower avg. SCS. Increased bedding depth measures tended to be associated with improved udder hygiene metrics. Although statistical power was limited, the current study provides insight on factors affecting bulk tank milk quality, udder health and hygiene measures on organic dairy farms in Vermont. Additionally, outcomes for bedded packs were comparable to more commonly used winter housing systems, and are therefore a viable option for pasture-based herds interested in a loose-housing system in the Northeast.

**Keywords:** Mastitis, organic dairy cattle, housing, bedded pack, milk quality

**Introduction**

Mastitis due to environmental pathogens, such as those commonly found in bedding material, has now become the “most common and costly form of mastitis in modern dairy herds” that have implemented standard mastitis control practices limiting the effect of contagious pathogens (Klaas and Zadoks 2018). Teats of dairy cattle may be in direct contact with bedding materials for 40 to 60% of the day, making this an important potential source of exposure to mastitis pathogens (Tucker and Weary 2004; Cook et al. 2005; Hogan and Smith 2012). Work exploring how bedding materials relate to a cow’s risk of getting mastitis has understandably been focused on the most commonly used bedding materials and housing systems in the dairy industry. There is growing interest and adoption of bedded pack systems to house dairy cattle. Smaller-scale dairy farmers with aging facilities may be looking to implement a bedded pack system on their farms as a sustainable, cost-effective, loose-housing option that integrates into pasture-based production systems, as both the dairy industry and consumers look to move away from traditional housing systems that restrict cow movement (Barkema et al. 2015). As interest in bedded pack housing grows, it will be important to better understand milk quality, udder health and hygiene on farms using these housing alternatives. The majority of previous work describing mastitis risk and cow hygiene in bedded pack systems has been descriptive studies of actively-managed, composting bedded packs (Barberg et al. 2007b; Black et al. 2013; Fávero et al. 2015; Eckelkamp et al. 2016b; Albino et al. 2018; Heins et al. 2019). Peer-reviewed publications of research comparing milk quality and cow hygiene between bedded pack systems and more traditional housing types has so far been limited, and includes a study comparing actively-managed composting bedded packs (CBP) and sand-bedded freestalls for farms with a history of low bulk tank somatic cell counts (Eckelkamp et al. 2016a), and a comparison of CBP and two types of freestall barns (Lobeck et al. 2011). It is unclear whether the herds included in these two studies were conventionally-managed or organic dairies. To the author’s knowledge, no studies describe and compare bulk tank milk quality, udder health and hygiene on bedded pack farms and tiestall barns of similar size and management style.

Organic dairies in the Northeast have expressed particular interest in bedded pack systems to house their cows, as these loose-housing structures are perceived to integrate well into pasture-based farm systems (Andrews et al., 2021). Currently, the most common type of dairy cattle housing for organic farms in Vermont is a tiestall barn, with freestall barns a distant second (Andrews et al. 2021). As consumer opinion about confinement housing of dairy cattle evolvesand influences dairy policy, small to mid-size dairy farms in the Northeast may be considering replacing their aging tiestall facilities. One option may be converting to a bedded pack system, as the initial investment is smaller than a new freestall barn (Bewley et al. 2012). Understanding mastitis risk for cattle housed on bedded packs will be especially important for organic dairy farmers, as they have limited effective options for treating intramammary infections (Ruegg, date). Previous research directly comparing bedded packs to other housing systems has been limited to freestalls with sand, which is an uncommon housing type for organic farms in Vermont (Andrews et al. 2021). A direct comparison of bulk tank milk quality, udder health and hygiene between bedded pack systems, freestall, and tiestall barns could provide valuable information about how this system performs in the Northeast.

In order to better inform organic dairy producers in the Northeast who may be interested in using a bedded pack barn for housing their cattle, we carried out a cross-sectional, observational study on organic dairies in Vermont. This study aimed to compare bulk tank milk bacteriology, udder health and hygiene measures for the two most common housing systems in the state for organic farms (freestalls, tiestalls) with farms using a bedded pack. The objectives of this project were to (1) identify whether bulk tank milk quality, udder health and hygiene outcomes differed by facility type; and (2) determine if bedded pack systems are a viable option for winter housing in VT. We hypothesized that udder health, hygiene, and bulk tank milk bacteriology would differ between housing types.

**Materials and Methods**

STROBE-VET (Strengthening the Reporting of Observational Studies in Epidemiology–Veterinary Extension) statement guidelines were followed in the reporting of this study (O'Connor et al. 2016).

1. **Herd enrollment and selection**

The source population for this study was the 145 farms that responded to a survey sent to all certified organic dairy farms producing cow milk in Vermont (n = 177). The survey aimed to quantify the frequency and diversity of winter housing and bedding types used by organic dairy farmers in the state (Andrews et al. 2021). Dairy farms were eligible for enrollment in the current study if they: 1) responded to the initial survey in the winter of 2018-2019, 2) indicated they met the enrollment criteria of testing with the Dairy Herd Improvement Association (DHIA) at least monthly, 3) milked between 35 and 120 cows, and 4) indicated they would be interested in further participation. Eligible farms were contacted from this source population if they responded that they were using one of four categories of bedding/housing combinations for their winter housing system: 1) freestall barn bedded with sand, 2) freestall barn bedded with shavings or sawdust, 3) tiestall barn bedded with shavings or sawdust, or 4) an enclosed loose housing facility deeply bedded with organic material (hereafter, “bedded pack”). The first three housing and bedding combinations were found to be the top three used by organic dairies in Vermont to house cows over the non-grazing season, and bedded packs were included as they were the primary housing style of interest for this project.

A convenience sample was enrolled in Spring 2019 from a list of eligible farms (grouped by housing/bedding combination) using the phone number or email address provided in the 2018-2019 survey. Our aim was to complete the current survey and sampling at 40 farms, with 10 farms from each of the four housing/bedding categories described above. As this study design was outlined before getting the full results from the 2018-2019 survey, and the University of Vermont Sustainable Agriculture Extension group had been promoting adoption of bedded-pack systems, it was anticipated that it would be possible to enroll 10 organic Vermont dairies using a bedded pack system as their primary winter housing system. However, out of the 17 farms from 2018-2019 survey that indicated at least some use of a bedded pack system, one farm was not interested in any further participation, five did not use DHIA testing, and six only used a bedded pack system as a secondary housing system in conjunction with a tiestall barn, or cows were only on the pack a few hours a day. Because the number of farms using bedded packs was significantly smaller than anticipated, the eligibility requirements were relaxed to include a farm where cows spend the majority (two-thirds) of their time in a bedded pack, with the remaining time in a tiestall with wood shavings. Additionally, two bedded pack farms were included that had limited DHIA information: one farm did not utilize cow-level testing, and cow-level data for a second farm was limited due to their seasonal lactation schedule. The survey was intended to study cows while they were in their winter housing system, so all herds visits were completed before any grazing had begun for the season.

Of the intended 40 herds to be recruited in the study 21 herds that were contacted agreed to participate and the survey and sampling were completed during April and May 2019. All herds sampled during this period were housing their cows as they would in the winter months. Completion of the survey and sampling was suspended in mid-May as farms began turning their cows out to pasture, with the intention of resuming in Spring 2020 to complete the remaining 19 herds. Due to the COVID-19 pandemic activity restrictions, the decision was made to not resume the survey and sampling, and the final analysis included the 21 herds sampled in 2019. As there was only one farm sampled using a freestall facility bedded with sand, the initial plan to group farms by the four housing/bedding combinations specified was abandoned in favor of grouping farms by the three facility types used [tiestall (TS), freestall (FS), and bedded pack (BP)].

1. **Survey administration, sampling, and udder hygiene scoring**

At each farm visit, a questionnaire was administered by the first author (CJ). The interview questionnaire collected information aiming to: 1) get a comprehensive understanding of factors potentially related to a cow’s mastitis risk on that farm, and 2) acquire a comprehensive understanding of housing and bedding management and related practices on the farm. The full survey is included in Supplemental Data (XXX). Survey and interview protocols were registered with the University of Vermont Institutional Review Board (IRB certification 19-0057). The survey was created and administered on a tablet using KoboCollect software (http://www.kobotoolbox.org). Questions about mastitis risk explored producer concerns about bedding/mastitis risk; mastitis control, identification and record keeping; milking facilities, procedures, and hygiene practices; information about diet, vitamin and mineral supplementation, and water source; typical calving and periparturient practices; and fly control. Questions about housing and bedding management included describing type of housing system used for both lactating and dry cows; classification and description of any bedding material used; and bedding management practices for each housing type used. The survey also collected some basic herd information (production numbers; number of lactating, dry, and youngstock; breeds; record-keeping systems). As the focus of this study was the use of bedded pack systems by organic dairy producers in Vermont, some additional questions were asked of these farms to gather more detailed information about bedded pack construction, management, monitoring, and perceptions comparing bedded packs to previously used systems. Completion of the survey took about 45 minutes on average, ranging from about 30 minutes to 1.5 hours.

At each farm visit, a co-author (TA) collected a bulk tank milk sample, bedding samples, and conducted a facility inspection. The bulk tank milk sample was collected directly from the top of the bulk tank after at least 5 minutes of agitation using a 250-mL sterile single-use vial (Blue Dippas™, Dynalon Products, England). Samples were kept on ice in a cooler until they could be frozen and stored at −20°C in the laboratory before being sent to a diagnostic lab for analysis. The facility inspection collected information about the bulk tank, cow identification, air quality, and any outdoor exercise area (supplemental data xxx). Measurements of the housing facilities were recorded for freestalls and tiestalls (stall sizes, pen sizes, bedding depth, stocking density, trainer use), as well as observations about bedded packs when applicable (temperature, depth, pen size, and stocking density m2 per animal). Bedding depth of freestalls and tiestalls was included as a producer reported value in the questionnaire. Bedding depth of bedded pack facilities was Udder hygiene scoring was completed by this co-author for a minimum of 30 randomly selected cows housed in the same pens from which used bedding samples were collected. A four-point udder hygiene scoring system was used, where 1 = free of dirt, 2 = slightly dirty (2–10% of surface area), 3 = moderately covered with dirt (10–30% of surface area), and 4 = covered with caked on-dirt (>30% of surface area) (Schreiner and Ruegg 2002). Materials were left with producers to record and collect milk samples of cows with clinical mastitis in the 30 days following the farm visit, but producer compliance in this aspect of the study was inconsistent and not included in any analyses. Animal use for this project was approved by the University of Vermont Institutional Animal Care and Use Committee (IACUC; protocol #PROTO202000089).

1. **Bulk tank milk culture and somatic cell count data**

An aliquot of bulk tank milk was stored at -4°C until it could be brought to the laboratory at a dairy processing plant (Dairy Farmers of America, St. Albans, VT) within 48 hours of collection for determination of the bulk tank somatic cell count (BTSCC).

Frozen bulk tank milk samples were shipped on ice to the Laboratory for Udder Health (University of Minnesota Veterinary Diagnostic Laboratory, St. Paul) for analysis. Methodology for bulk tank milk cultures at the Laboratory of Udder Health are described elsewhere (Patel et al. 2019). Briefly, thawed, room-temperature bulk tank milk and a 10-fold dilution of each bulk tank milk sample were plated onto MacConkey, Factor (gram-positive selective agar; University of Minnesota, 2016), and Focus (University of Minnesota, St. Paul, selective for SSLO bacteria) media plates and incubated for two days at 37°C. Any lactose-fermenting colonies on MacConkey medium were counted and reported as coliform bacteria. Any β-hemolytic colonies on Focus medium were counted and identified to the species level using a MALDI Biotyper (suspect *Streptococcus agalactiae*). All remaining colonies on Focus medium that were not identified as *Strep. agalactiae* were counted and recorded as streptococci or strep-like organisms. Hemolytic colonies on Factor medium were counted and identified to the species level using a MALDI Biotyper (suspect *Staph. aureus*). Any hemolytic colonies with a confidence score ≥2.0 for *Staph. aureus* were counted and reported as such. Remaining colonies of staphylococci on Factor media (based on colony morphology, catalase reaction, or Gram stain) were counted and reported as non-*aureus* staphylococci. Bulk tank samples were also cultured for *Mycoplasma* spp. (0.1 mL milk was swabbed across a Mycoplasma agar plate, then placed in a 7% CO2 incubator at 37°C for 7 days, after which they were examined for *Mycoplasma* spp. by a trained microbiology technician). For each bulk tank milk sample, total colony-forming units (CFU) per mL were calculated for coliform organisms, non-*aureus* staphylococci (NAS), streptococci and strep-like organisms (SSLO), *Staph. aureus*, *Strep. agalactiae*, and *Mycoplasma* spp. The lower threshold of detection for bacteria in this bulk tank milk culture protocol was 5 cfu/mL, and the upper threshold was 62,500 cfu/mL.

1. **Herd-level udder health measurements**

Herd-level DHIA test results for the test day closest in time to the farm visit (less than 30 days) were captured from the record processing center working with each herd (Lancaster DHIA, Manheim, PA; Dairy One Co-Op. Inc., Ithaca, NY). Information captured included test dates, number of lactating cows, standardized 150-day milk production, and test-day average cow-level somatic cell score (SCS). The following udder health measures were also captured from DHIA records: proportion of cows with an SCC ≥200,000 cells/mL on most recent test day (“elevSCS”), where elevated SCS was defined as a somatic cell score of ≥4.0; the proportion of cows with a newly-elevated SCS (“newSCS”), which was defined as a SCS changing from <4.0 to ≥4.0 over the last 2 tests; and the proportion of cows with a chronically-elevated SCS (“chronSCS”), which was defined as having a SCS ≥4.0 on the last two tests (Schukken et al. 2003).

1. **Data management and analysis**

Survey data collected through KoboCollect software (KoboCollect 2019) was downloaded as an Excel worksheet (Microsoft Corp., Redmond, WA), which contained the information from the questionnaire covering herd information, description of housing and bedding management, milking hygiene, and mastitis control practices. Udder hygiene scores for individual cows were used to calculate two farm-level udder hygiene measures: 1) mean udder hygiene score, and 2) proportion of cows with dirty udders (udder hygiene score ≥3). Bulk tank milk culture data from the U. Minnesota Veterinary Diagnostic lab, BTSCC, DHIA test results, and farm-level udder hygiene outcomes were entered into an Excel database that included the accompanying data for each farm from the questionnaire and farm inspection. This Excel database was then imported into the R Statistical Programming Environment (R Core Team, 2023) for data cleaning, checking, and statistical analysis. The distribution of outcome variables was visually assessed in R to check for normality, and descriptive statistics were calculated to evaluate the distribution and data integrity and to identify missing data (means, variances, percentiles for numeric continuous variables, frequencies tabulations and percentages for categorical variables). Descriptive statistics generated included description of general herd characteristics/farm traits, lactating cow housing/facilities, lactating cow bedding material/bedding management practices, milking hygiene procedures, and mastitis control practices for all 21 herds included in the study. Additionally, descriptive statistics were also produced to describe udder hygiene, bulk tank milk quality and bacteriology, and DHIA udder health outcomes, for all herds (n = 21) and for herds stratified by facility type (freestall, bedded pack, tiestall). Distribution of the raw bulk tank somatic cell count (BTSCC) data, log2 transformed BTSCC data, and log10 transformed BTSCC data was assessed, and all were found to be similarly close to being normally distributed; therefore, the raw BTSCC data was chosen for ease of interpretation.

Unconditional comparisons of bulk tank udder health measures, aerobic culture data, and hygiene scores by facility type were then carried out using an appropriate test. Bulk tank somatic cell count, newSCS, chronSCS, elevSCS, STD 150-day milk, mean hygiene and proportion dirty udders met the assumptions for a One-way Fisher’s ANOVA (no outliers, normality using a Shapiro-Wilk test at p ≤0.05, and homogeneity of variances using both Levene’s test and visual assessment of a residuals vs. fitted values plot). The Tukey method was used for adjusting p-values for multiple comparisons (“TukeyHSD” function of the “stats” package in R). As most measures of aerobic culture data were not normally distributed even after log transformation, a Kruskal-Wallis test was used to compare CFU counts between the three facility types. Welch’s ANOVA was used for analysis of average SCS, as the data were normally distributed but had unequal variances. Statistical significance for ANOVA and Kruskal-Wallis tests were declared at *P* ≤0.05.

Continuous variables underwent correlation analysis to identify predictor variables that were highly associated (correlation coefficient ≥ 0.60), and unconditional associations among categorical variables were evaluated using a Pearson’s chi-squared or Fischer’s Exact test as appropriate (*P* ≤ 0.05). An ANOVA was used to check for correlation between numeric continuous variables and categorical variables (*P* ≤ 0.05). When a categorical variable had multiple groups with a small number of observations in each, groups were combined when biologically reasonable to have all categories of predictor variables contain at least five observations. If any predictor had only one observation in a group and there was no way to combine groups in a logical way, it was excluded from further analysis (but listed in descriptive statistic tables).

Univariate linear regression was performed in R using the “lme4” package to investigate the unconditional relationship between the six udder health and production outcomes (BTSCC, avg. SCS, newSCS, elevSCS, chronSCS, STD 150-day milk) and two hygiene outcomes (mean hygiene score, proportion of dirty udders) for each farm and the previously-described herd-level independent variables. The two udder hygiene metrics (proportion dirty udders and average udder hygiene score) were used as both predictor variables (in models for other outcome variables) and outcome variables in models of their own. Any explanatory variable that was unconditionally associated with 1 or more of the outcomes of interest at *P* < 0.20 was then offered into a multivariable model investigating the relationship between the udder health and production or hygiene outcome and the herd-level predictor variables. If any predictor variables were found to be correlated with each other, the one with the more highly significant relationship from univariate analysis was offered to the multivariable model. The two udder hygiene metrics were highly correlated (derived from the same data), so whichever one had a smaller *P-*value from the univariate analysis was chosen for inclusion in the model-building process. Facility type was forced into these multivariable models, as it was the primary explanatory predictor of interest. A backward stepwise variable selection process was then used, with the least significant variables being removed one by one until all remaining predictors had *P* ≤ 0.10.

The multivariable modelling approach aimed to investigate the conditional relationship between facility type and the eight outcomes of interest while controlling for different farm management practices, housing characteristics, milking procedures and mastitis control practices. However, due to the limitations of the data set and small facility group size, select results of the univariate analysis (grouping all 21 farms together) using linear regression between independent predictors and outcomes of interest is also reported. Unconditional relationships between the eight outcome variables and independent predictors are reported for a significance level of *P* ≤ 0.20, and only for predictor variables with group sizes of at least n = 5.

**Results**

1. **Description of study herds**

Of the 21 herds enrolled five used a bedded pack system, one used a freestall bedded with sand, 5 used a freestall bedded with shavings/sawdust, and 10 used a tiestall bedded with shavings/sawdust (Supplemental Table S1). Two bedded pack farms bedded with shavings/sawdust and cultivated 2 times a day to promote aerobic composting, 1 farm bedded with straw and woodchips and cultivated 2 times a week, and 2 bedded pack farms bedded mainly with straw, adding woodchips as needed, and did not cultivate the pack at all. The predominant breeds for the farms were Holstein (n = 8 farms), Jersey (n = 10), and mixed Holstein-Jersey crosses/other (n = 3). The median (mean; range) number of lactating cows was 68 (64.9; 32-99). The median annual rolling herd average milk production for the farms was 14,037 (14,163; 9,000-21,204) pounds. Nineteen of the 21 farms tested with DHIA monthly while their cows were in milk, with one farm testing 5-8 times/year and one testing every other month. Detailed descriptions further characterizing study farm management practices and housing characteristics for lactating animals (e.g., laying surface, ventilation, stocking density), and details about bedding material and bedding management practices for lactating animals (e.g., bedding depth, frequency of adding new bedding, manure removal) are provided in Supplemental Tables S1 and S2, respectively. Detailed descriptions of routine milking procedures and mastitis control practices are provided in Supplemental Tables S3 and S4, respectively.

1. **Comparison of bulk tank milk aerobic culture data**

None of the 21 bulk tank milk samples were positive for *Strep. agalactiae* or *Mycoplasma* spp. Results of aerobic culture are presented in Table 1. Sixteen of the 21 bulk tank milk samples were negative for coliforms on aerobic culture, while 5 farms had a coliform count of 5 cfu/mL. *Staph. aureus* was found in the bulk tank milk from 13/21 herds, with a median (mean; range) cfu/mL of 50 (70; 15-320) when present. The median (mean; range) *Staph.* spp. count found in the 21 bulk tank milk samples was 65 (96; 0-665) cfu/mL, while the median SSLO count was 45 (156; 10-1,250) cfu/mL.

1. **Comparison of bulk tank milk udder health measures by facility type**

The mean (SD; range) raw somatic cell count for the 21 bulk tank milk samples collected was 144,286 cells/mL (53,934; 54,000-250,000) (Table 2). For the 19 herds with available DHIA test-day data, the mean percent of cows with newly-elevated SCS was 5.7 (3.7; 0-12.3), mean percent of cows with chronically-elevated SCS was 13.6 (5.8; 2.9-23.1), and mean percent of cows with elevated SCS was 25 (7.8; 8.6-36.9). For the 18 herds with available data, mean standardized 150-day milk was 50 pounds (10.1; 33.5-68). For the 20 herds with available cow-level test data, the average SCS was 2.44 (0.42; 1.7-3.3).

1. **Comparison of udder hygiene scores by facility type**

The overall mean (95% CI) of herd-level udder hygiene scores for all 21 farms was 2.32 (2.16-2.49). The mean (95% CI) hygiene score was 2.2 (1.91-2.44) for bedded pack farms (n = 5), 2.5 (2.24-2.76) for tiestall farms (n = 10), and 2.15 (1.93-2.37) for freestall farms (n = 6). A one-way Fisher’s ANOVA revealed that there was no difference in mean hygiene score of cows in a herd between the three facility types [F (2,18) = (2.307), *P* = 0.13].

The overall mean (95% CI) proportion of cows with dirty udders in a herd (udder hygiene score ≥3) was 40% (31-48%). The mean proportion of cows with dirty udders (95% CI) was 32% (18-46%) for bedded pack farms (n = 5), 49% (35-62%) for tiestall farms (n = 10), and 32% (20-44%) for freestall farms (n = 6). A one-way Fisher’s ANOVA revealed that there was no difference in proportion of cows with dirty udders in a herd between the three facility types (F(2,18) = [2.1031], *P* = 0.15).

1. **Results of multivariable analyses for udder health and hygiene outcomes**

As the main predictor of interest to the study, facility type (FS, TS, or BP) was forced into the model for each of the eight outcomes, but was not found to be a significant predictor in any model. For all models, numerous variables that were unconditionally associated with an outcome but correlated with another independent variable offered into the model had to be excluded in order to prevent multicollinearity. In this instance. the variable with a lower *P*-value for an unconditional association with an outcome was chosen for inclusion. For the models exploring newSCS, chronSCS, and elevSCS, 2 bedded pack farms did not have available DHIA data (group sizes: FS =6, TS = 10, BP = 3). For STD 150 milk, 1 bedded pack farm and 2 tiestalls were missing DHIA data (group sizes: FS = 6, TS = 8, BP = 4). One bedded pack farm did not have average cow-level SCS data (group sizes: FS = 6, TS = 8, BP = 4). All 21 farms were able to be included in the models for BTSCC, average hygiene score, and proportion of dirty udders.

Predominant breed (Holstein, n = 8; Jersey/Other, n = 13) and herd size (n = 21) were offered to a multivariable model for BTSCC. No models were produced for BTSCC that were statistically significant overall (F-test, *P* >0.05) or which had any significant predictors.

Herd size category (30-55 cows, n = 5; 56-69 cows, n = 6; 70-100 cows, n = 8), use of bedding conditioner (y = 5; n = 14), air quality as assessed by researcher (“fair,” n = 5; “good,” n = 14), glove use at milking (always = 9; no/inconsistently = 9), and clinical mastitis record keeping practices (always kept records of mastitis event = 7; never kept record = 6; sometimes/kept records temporarily = 6) were offered to a multivariable model for newSCS. The model with the lowest AIC value (91.36) was an improvement on the reduced model with only facility type (ANOVA, *P* =0.01), and included bedding conditioner use, air quality, glove use, and mastitis record keeping practices. However, this model was only a marginal improvement on the full model (AIC = 91.76). Bedding conditioner use and air quality were significant predictors in this best model, which overall was significant at *P =*0.014.

Feeding additional supplemental selenium (y = 11; n = 7), use of bedding conditioner (y = 5; n = 14), udder hair clipping (y = 5; n = 14), and proportion of dirty udders (n = 19) were offered to a multivariable model for chronSCS. The full model was the best, was significant overall (*P* =0.04), and was an improvement on the reduced model (ANOVA, *P* =0.02), but the only predictor found to be significant was the proportion of dirty udders (*P* = 0.018).

For modelling elevSCS, bedding conditioner use (y = 5; n = 14) and mean hygiene (n = 19) were offered. No models were produced that were statistically significant overall, and none had any significant predictors (*P* >0.05).

Feeding additional supplemental selenium (y = 11; n = 8), use of bedding conditioner (y = 5; n = 15), use of organic approved intramammary product at dry-off (y = 5; n = 15), use of injectable selenium and vitamin E product (never = 11; regularly/occasionally = 9), and mean hygiene (n = 20) were offered to a multivariable model for herd average SCS. The best model for avg. SCS included use of bedding conditioner, dry product, injectable selenium, and mean hygiene score, with all predictors except use of dry product found to be significant. Overall, this model was significant (*P* =0.01), and shown to be better than the reduced model (*P* =0.003).

For modelling STD 150-day milk, use of injectable selenium and vitamin E product (never = 11; regularly/occasionally = 7), whether producers cultured high SCC cows (always/sometimes = 8; never = 10), and herd size category (30-55 cows, n = 5; 56-69 cows, n = 5; 70-100 cows, n = 8) were offered. No models statistically significant overall, and none had any significant predictors (*P* >0.05).

The only predictor offered to the model for proportion of dirty udders was air quality assessed by researcher (“fair,” = 5; “good,” =16). The model was not significant, and was no better than the reduced model only containing facility type (*P* >0.05).

For modelling average hygiene score, the predictors meeting the threshold to be offered to the model were whether the producer ever cultured quartermilk samples (never = 7; sometimes/regularly = 14) and whether the producer generally followed recommended practices for mastitis control (y = 8; n = 13). No models were statistically significant overall, and neither predictor was significant (*P* >0.05).

1. **Results of univariate analyses for udder health and hygiene outcomes**

Selected results of univariate analysis identifying factors unconditionally associated with udder health and hygiene outcomes at *P* <0.20 are presented in Table 3. The depth of bedding in stalls for freestall and tiestall herds was unconditionally associated with multiple udder health outcomes. For freestall and tiestall herds, as the depth of bedding in stalls increased, udder health measures improved (lower SCS, BTSCC, elevSCS, and newSCS). Similarly, herds where cows were on deep bedding (deep-bedded freestalls and bedded packs) had a lower BTSCC compared to herds that had stalls with a smaller amount of bedding on top of a mattress or concrete.

Udder hygiene measures were associated with numerous udder health outcomes. Higher mean hygiene scores and proportion of udders scored ≥3 tended to be associated with higher chronSCS (*P*=0.05 and 0.05, respectively), elevSCS (*P*=0.09 and 0.13, respectively), and average SCS (*P=*0.11 and 0.12, respectively) (table 3). A few specific management practices were also found to be unconditionally associated with udder health outcomes: consistent glove use was associated with lower newSCS, clipping or flaming udders was associated with fewer chronSCS, and both parenteral supplementation of a vit. E/selenium product and use of an non-antibiotic intramammary product at dry-off were associated with lower average SCS (table 3).

Both udder hygiene outcomes were unconditionally associated with the same predictors, most of which were related to the depth of bedding for cows. For herds using a bedded pack, deeper bedding was associated with lower average hygiene scores (*P*=0.008) and lower proportion of dirty udders (*P*=0.004) (Table 3). Farms with cows housed on some type of deep bedding (i.e., grouping all herds reporting deeply-bedded stalls plus bedded pack herds) tended to have lower average hygiene scores (*P* =0.06) and proportion of dirty udders (*P* =0.06), compared to herds housing cows on stalls with bedding on a mattress or concrete surface (Table 3). For the fifteen farms reporting bedding depth in stalls, increased bedding depth tended to be associated with both lower mean udder hygiene score (*P*=0.07) and lower proportion of dirty udders (*P*=0.13) (table 3).

**Discussion**

The current work presents the results of our observational study exploring udder health and hygiene metrics, bulk tank milk quality, and aerobic culture data on small-midsize organic dairy farms in Vermont. The objective was to identify whether these outcomes were associated with facility type, and whether bedded pack systems are a viable option for winter housing in Vermont when compared to the two most common winter housing systems in the state (freestalls, tiestalls). As bacteriology, udder health and hygiene metrics for bedded packs did not differ compared to tiestall and freestall herds included in the current study, there was insufficient evidence to reject our hypothesis that these metrics would vary by facility type. We therefore feel that bedded pack systems can be considered a viable loose-housing option for the winter in the Northeast.

1. **Bulk tank milk aerobic culture data by facility type**

Previous work describing bulk tank milk aerobic culture data for farms using a bedded pack system has primarily been limited to descriptive studies enrolling only composting bedded pack herds (Barberg et al. 2007b; Shane et al. 2010), with only one study directly comparing bacterial counts between composting bedded packs and freestall barns (Lobeck et al. 2012). The current study is the first the authors are aware of directly comparing bacterial counts of bulk tank milk between bedded packs (both composting and static) and tiestall barns, and the first one to describe a population of exclusively organic dairies. In contrast to previous work, which evaluated milk culture results across the summer months (Barberg et al. 2007b) and year-round (Lobeck et al. 2012), the current study focused solely on sampling during the winter months. The authors were most interested in studying bulk tank milk bacteriology for these organic herds during the winter months, during the time these primarily pastured-based farms need to house their animals inside. Comment on all herds excellent bulk tank milk quality – fall in the low category of Jayarao et al. 2004

The *Staph.* spp. count for the five bedded pack farms included in this study (53 CFU/mL, 95% CI: 10-96) was comparable to previous work describing bulk tank milk quality for composting bedded packs in Minnesota which also collected samples during the winter months. The six farms included in Lobeck et al. (2012) used mainly wood sawdust as a bedding source (with one using a wheat straw by‐product), similar to our current study where three of five bedded packs using a combination of woodchips/shavings and straw/hay, and two using exclusively sawdust/shavings). The six farms included in the study by Shane et al. (2010) bedded with a variety of “alternative” organic materials, including straw by-products, soybean stubble, and oat hulls. Lobeck et al. 2012 found a mean of 26.1 CFU (95% CI: 2-443) and Shane et al. (2010) found a range of 0-108 CFU/mL for *Staph.* spp. from BTM collected during the winter from six composting bedded pack farms. Comment of sources of CNS/NAS and diversity of species and unknown relationship between species and source – also importance of milking hygiene skin commensals lack of knowledge how bedding management contributes.

Streptococci and strep-like organisms (SSLO) counts in BTM for bedded packs in the current study were much lower than those from Minnesota composting bedded packs in the winter. Shane et al. 2010 reported a range ofSSLOcounts of 98-48,400 CFU/mL for six farms, and Lobeck et al. 2012 reported a mean of 911 CFU/mL (95% CI: 138-6,011). The mean SSLO counts for bedded pack farms included in the current study was 39 CFU/mL (95% CI: 17-61). Work from Barberg et al. (2007) describing milk quality on composting bedded packs in Minnesota noted that 6 of 12 farms sampled had “high” levels of SSLO. The overall SSLO count for all 21 farms included in the current study (156 CFU/mL, 95% CI: 42-271) was much lower than that for the overall *Strep.* count for all three facility types studied in Lobeck et al. 2012 (445 CFU/mL, 95% CI: 116-1704). As the overall SSLO counts for all farm types included in the Minnesota studies are higher than that found for all 21 farms in the current study, better milking and bedding hygiene amongst herds included in this study may best explain this difference in BTM pathogen profiles (Jayarao and Wolfgang 2003).

All farms included in the current study had low levels of coliforms in bulk tank milk (1.2 CFU/mL, 95% CI: 0.3-2.1), indicating excellent hygiene practices at milking time (Jayarao and Wolfgang 2003). Bedded pack farms in the current study had very low coliform counts in BTM (1 CFU/mL, 95% CI: 0-3), similar to those found for three compost bedded pack farms in a Brazilian study (2.8 CFU/mL; Fávero et. al 2015). These low coliform counts are in contrast with previous work describing BTM quality for this kind of facility in the United States. Coliform counts for bedded packs in Minnesota in the winter ranged from 15-1,128 CFU/mL (Shane et al. 2010), and had a mean of 63.7 CFU/mL (95% CI: 6-735) for the six bedded packs included in Lobeck et al. 2012. However, direct comparison of coliform counts between studies may be potentially problematic due to variation in duration of freezer storage (Schukken et al. 1989). Although sampled during summer months, Barberg et al. 2007 found that 5 of 12 bedded packs sampled had “high” levels of coliforms in BTM, contributing to their conclusion that “special attention to cow preparation procedures at milking time are a must for achieving satisfactory milk quality when cows are housed in compost dairy barns.”

Although not statistically significant, the mean *Staph. aureus* cfu count in BTM for bedded pack farms was numerically smaller than that for tiestalls and freestalls. The bedded pack category had the highest proportion of farms with BTM negative for *Staph. aureus* (60% for BP, vs. 33.3% for both TS and FS). As *Staph. aureus* is regarded mainly as a contagious mastitis pathogen, on-farm prevalence is more likely a function of milking time hygiene and other management practices associated with limiting cow-to-cow transmission vs. environmental factors (i.e., bedding material type and hygiene; Jayarao and Wolfgang, 2003; although, recent studies have described environmental reservoirs of transient sources and stall design and management influences this (Leuenberger et al., 2019). The lower prevalence of *Staph. aureus* on bedded pack farms in the current study may be a function of confounding. Producers using this less-traditional housing type (bedded packs) are inherently more open to newer technologies (need a reference here). A Dutch study found more progressive dairy farmers (younger in age, had children with higher education levels, more likely to invest in the future for their farm) were more likely to have a lower bulk tank milk somatic cell count (Barkema et al. 1998). We speculate that an extension of this relationship is that the progressive dairy farmers already using a bedded pack may be more likely to have implemented stricter control programs for contagious mastitis pathogens such as *Staph. aureus*. Prevalence of *Staph. aureus* was similar between the five VT bedded pack farms in the current study (9 CFU/mL, 95% CI: 0-21) and the six bedded packs described in Lobeck et al. 2012 (6.2 CFU/mL, 95% CI: 1.3-30.1). Farm-level prevalence of *Staph. aureus* was also fairly low for bedded packs studied in Shane et al. 2010 (3 of 6 farms BTM negative) and Barberg et al. 2007 (only 1 of 12 farms with a “high” level of *Staph. aureus*). Overall, the population of all 21 farms in the current study had a higher amount of *Staph. aureus* in BTM than the 18 Minnesota farms described in Shane et al. 2010 (43.6 CFU/mL, 95% CI 14-73; vs. 17.3 CFU/mL, 95% CI: 3.3-91.2). Although it is not clear how many herds included in previous work on bedded packs were certified organic, the higher prevalence of *Staph. aureus* amongst farms in the current study is consistent with work comparing organic and conventional dairy systems (Pol and Ruegg 2007).

Analysis of a single bulk tank milk sample from a farm is a simple, convenient, and relatively inexpensive way to capture a snapshot of current milk quality and animal health on a farm, and can be a highly specific (albeit poorly sensitive) screening test for major contagious mastitis pathogens (*Staph. aureus* and *Strep. agalactiae;* (Godkin and Leslie 1993). Our bulk tank sampling strategy (collecting a single sample) differs slightly from previous work describing the bacteriology of milk from bedded pack farms, where four or five consecutive bulk tank milk pickups were collected and then pooled for analysis (Barberg et al. 2007b; Shane et al. 2010; Lobeck et al. 2012). However, the aerobic culture methodology (all carried out at the Laboratory for Udder Health, University of Minnesota) following collection was very similar between studies, hopefully facilitating direct comparisons.

We acknowledge that analysis of a single BTM sample comes with limitations. Bacterial groups traditionally considered to be primarily environmental in origin (non-*ag. Strep.,* non-*aureus Staph.,* coliforms), may enter BTM from cows with an intramammary infection, but also may originate from non-specific contamination (teat and udder skin, bedding, manure, or other environmental sources). Furthermore, a single bulk tank sample does not give insight into long-term, consistent patterns of a particular farm’s milk quality as is possible from repeated BTM samplings (Jayarao and Wolfgang 2003). With the financial constraints of research on commercial dairy farms, the limitations inherent in performing analysis of a single bulk tank milk sample from each farm were a trade-off for the ability to get a picture of milk quality on a larger number of farms included in the study.

1. **Univariate analysis of bulk tank milk udder health and hygiene measures**

As results from the multivariable models exploring the effect of facility type suffered from limited statistical power due to small sample sizes, the focus of the discussion will be on trends that emerged from the univariate analysis which combined all 21 farms. The two udder hygiene metrics (proportion dirty udders and average udder hygiene score) shared many of the same associations with other variables, as they are highly correlated.

One theme emerging from this work is that farms with deeper bedding had more favorable udder hygiene metrics (deeper bedding begets cleaner cows). When comparing farms that housed cows with a deep bedding system (deeply-bedded stalls or a bedded pack) to those that housed cows on stalls with a smaller amount of bedding (over a mattress or concrete surface), the deeply-bedded systems tended to have better hygiene scores. This agrees with previous work in freestall barns including: Cook et al. 2016 (prevalence of dirty udders was 13% lower for farms using deep bedding vs. stalls with mats), de Vries et al. 2015 (deep-bedding vs. mat/mattress reduced the likelihood of a cow having a dirty hindquarter by half), and Robles et al. 2020 (farms with mattress-based stalls had a higher prevalence of cows with dirty upper legs/flanks vs. those using a deep bedding system, often inorganic sand). In contrast, research looking at the effect of bedding depth in tiestalls found no difference between leg, flank, and udder hygiene of cows using deeply-bedded stalls (14 cm) and the control treatment (2-3 cm; Wolfe et al., 2018).

Beyond comparing udder hygiene of cows housed on a deep-bedding system to cows that were not, there was a linear association between bedding depth (depth of bedded pack, depth of bedding in freestalls and tiestalls) and hygiene score. As the measured height of bedding got deeper (height of bedded pack, or amount of bedding material in stall), cows tended to have cleaner udders. Work exploring this direct relationship between different bedding depths and hygiene is limited to a single study by de Vries et al. 2015, who found no relationship between prevalence of dirty hindquarters and three different freestall bedding height groups (<0.56 cm, 0.56–1.75 cm, >1.75 cm). In our study, this relationship between bedding depth and udder hygiene was especially strong for the bedded pack herds, despite the limited sample size of five herds. To the best of our knowledge, this specific relationship has not previously been explored for bedded pack herds. There is clearly great opportunity for future research looking at the trade-off between increased bedding costs for deep-bedded systems (or just more deeply-bedded stalls) and the benefit of improved udder hygiene and milk quality.

Multiple measures of udder health in this work were related to udder hygiene, in accordance with the well-supported tenet that better cow hygiene is associated with better milk quality (cleaner cows beget better milk). This association between an animal’s hygiene and udder health has been well-documented, both at the cow level (for IMI presence: de Pinho et al. 2012; for SCS/SCC: Reneau et al. 2005, Dohmen et al. 2010, and Sant’anna et al. 2011; for both SCS and IMI: Schreiner and Ruegg, 2003) and at the herd-level (BTSCC: Barkema et al. 1998; new IMI rate: Cook et al. 2002; average herd SCC, incidence clinical mastitis, and % new high SCC: Dohmen et al. 2010). Of particular relevance to the current work, a study carried out on three bedded pack farms in Brazil found the odds of a new case of subclinical mastitis (SCC ≥200,000 cells/mL) and of a cow having subclinical mastitis on test day increased 32% and 16% for each one-unit increase in leg cleanliness score, respectively (Fávero et al. 2015). Curiously, although leg cleanliness score was associated with both mastitis outcomes on Brazilian bedded packs, udder hygiene score was not.

A third predominant theme to emerge from the univariate regression results is that farms using deeper bedding had better milk quality outcomes (deeper bedding begets better milk). Although there is an established recommendation of 15 cm for deep bedding of freestalls (Bickert 2000; Cook 2002), this depth appears to be based on optimizing cow comfort in deep-bedded freestalls with no relevance for udder hygiene or health. There is very limited work exploring ideal bedding material depth for tiestall barns (Tucker and Weary 2004; Tucker et al. 2009), and this is again solely focused on the important concern of cow comfort. As is the experience of the authors, and is stated elsewhere in a literature review by McPherson (2020), “…very little research has investigated the effect of bedding depth on cow cleanliness” or considerations around udder health outcomes. It is likely that the effect seen in the current work of deeper bedding and better udder health outcomes is mediated through the preestablished effects of (1) deeper bedding leading to improved hygiene, and (2) improved hygiene resulting in better udder health. Even still, the opportunity exists for research exploring optimal stall bedding depths of different organic materials in tiestall barns with a focus on mastitis and udder health outcomes. It may be that recommending a particular depth of bedding to use for different types of organic material would not prove feasible, as the ideal amount would vary with many factors particular to a producer’s barn and bedding source (type of stall surface, presence/type of stall mat used, type of organic material, particle size, compressibility, percent dry matter, etc.).

1. **Unconditional comparison of bulk tank milk udder health, production, and hygiene measures by facility type**

There was no difference in the two udder hygiene measures (proportion of udders scored ≥3, average udder hygiene score) between the three facility types included in the study (tiestalls, freestalls, bedded packs). This finding is in accordance with previous work, which found that cow hygiene on bedded pack systems was comparable to traditional facility types in the Upper Midwest of the US, Kentucky, and Brazil (Barberg et al. 2007b; Shane et al. 2010; Lobeck et al. 2011; Black et al. 2013; Eckelkamp et al. 2016b; Eckelkamp et al. 2016a; Costa et al. 2018; Andrade et al. 2022). In comparison to some previous work comparing different hygiene measures of dairy cows between facility types, only udder hygiene was measured in the current study. Other researchers studying this issue have taken a more comprehensive evaluation of dairy cow hygiene, including separate scores for different body regions (lower legs, upper legs, udder, flank, and belly). Cook (2002) has pointed out the challenges of comparing dairy cattle hygiene between different facility types; namely, cows in freestall barns tend to have dirtier lower legs from walking through alleyways, whereas tiestall cows are likely to have dirtier upper legs and flanks, and loose-housed cows may have a different pattern of manure deposition on their bodies depending on the cleanliness of their lying surface. Despite the limitation of only observing udder hygiene, we feel confident that udder hygiene of cows housed on bedded pack systems in the current study was comparable to the more conventional housing systems used by dairies in the Northeast. Leso et. al (2020) point out that cow hygiene is highly dependent on conditions of the bedded pack, especially the moisture content. Black (2013) and Eckelkamp (2016a) reported that increased pack moisture allows wet bedding material and manure to adhere more easily to animals, therefore increasing hygiene scores. This sentiment was echoed by the bedded pack producers in the current study, who shared that keeping their cows clean during periods of wet or humid weather could be a challenge. However, with proper management and attention to detail, all bedded packs in the current study had an average udder hygiene score of less than 2.5 and the farm with the lowest mean average udder hygiene score overall was a bedded pack farm.

STD 150-day milk production did not differ between facility type in the current study (BP: 46.9 lbs., TS: 49.4 lbs., FS: 53.0 lbs.). This aligns with previous research, which found no significant differences in various production metrics of cows housed on bedded packs vs. in freestall barns (Lobeck et al. 2011; Eckelkamp et al. 2016a; Costa et al. 2018). Different studies have reported varying production metrics for cows housed on bedded packs (kg/cow/day, fat-corrected milk/cow/day, average L/cow/day, ME-305, rolling herd average, energy-corrected milk), preventing direct comparison of milk production between the bedded packs in the current study and previous work. Furthermore, many variables play a role in determining milk production per cow (nutrition, breed, seasonality, DIM, etc.), so teasing out the effect of facility type alone on production in an observational study is difficult. However, as Leso et. al (2020) point out, the “results in the literature indicate that high levels of milk production are possible in CBP,” and, as bedded packs potentially improve cow comfort, we may even expect greater milk production than in more traditional housing systems (Calamari et al. 2009; Ruud et al. 2010).

Udder health outcomes included in the current study (percent cows with elevSCS, percent cows with chronSCS, percent cows with newSCS, BTSCC, and average SCS) did not differ significantly between facility types. Although some previous groups have found BTSCC to be elevated for CBP farms (425,000 cells/mL over all four seasons, Black et. al 2013; 325,000 cells/mL during summer months, Barberg et. al 2007b), other groups have also found that udder health and milk quality measures on bedded pack farms are similar to that found on farms using more traditional facility types. Specifically, subclinical mastitis prevalence levels did not differ between compost bedded packs and two types of freestall housing in Minnesota and South Dakota, where the percent of cows in a herd with an SCC on test day ≥200,000 cells/mL was 33.4, 26.8, and 26.8% for compost bedded packs, cross-ventilated freestalls, and naturally-vented freestalls (Lobeck et al. 2011). Eckelkamp et. al 2016a found no significant difference in subclinical mastitis prevalence in low-SCC CBP vs. sand-bedded freestalls in Kentucky (21.8 and 19.4%, respectively), as well as no difference in BTSCC between the two facility types (229,582 and 205,131 cells/mL, respectively). Subclinical mastitis prevalence was 27.7% for 12 CBP farms in Minnesota (Barberg et. al 2007b), which may be more representative of the general population of bedded pack farms in that state as there were no inclusion criteria around maintaining a low SCC previous to the start of the study. The prevalence of subclinical mastitis for herds in the current study is comparable to the previous work in the US cited above, with a prevalence of 26% for farms using a bedded pack and 23.7% for freestall barns. In contrast, Fávero et. al (2015) found a much higher prevalence of subclinical mastitis (43.8%) and percent new infections (20.9%) for three bedded pack farms in Brazil than the current study (26 and 7% respectively, for the three bedded packs with available data).

Recent previous work has exclusively focused on describing bedded packs that are actively managed for aerobic composting (Leso et al. 2020). Leso et al. contrasted composting bedded packs (CBP) managed with daily cultivation with conventional bedded packs, such as straw yards, noting the reduced cow cleanliness and increased risk of mastitis associated with the latter. While bedded pack systems are not common for housing lactating cows in Vermont, both composting and static systems are used (Andrews et al. 2021). This infrequent use of bedded packs in our state created a challenge for enrolling ten herds using this kind of system in our observational study. Despite this limitation, by including bedded pack farms managed in a variety of ways, the current work sheds light on a broader spectrum of options used within this loose-housing system. Our current study shows that, with careful management of bedding material and excellent milking hygiene practices, farms are capable of achieving excellent milk quality using either a static or aerobically composting bedded pack system for winter housing. Three of the five bedded pack farms achieved a BTSCC of below 99,000 cells/mL, and the remaining two were below 200,000 cells/mL. Furthermore, the lowest BTSCC in the study (54,000 cells/mL) was achieved by a bedded pack farm using woodchips and straw which was not actively managing the pack to compost.

As udder health and hygiene metrics for bedded packs did not differ compared to tiestall and freestall herds included in the current study, we feel that bedded pack systems can be considered a viable loose-housing option for the winter in the Northeast. These systems have a number of advantages for producers considering updating their facilities, including a smaller initial investment when compared to a new freestall or tiestall barn (Barberg et al. 2007a; Janni et al. 2007; Black et al. 2013), although the cost year-over-year for bedding is substantial (Shane et al. 2010). From the perspective of animal welfare, bedded packs provide a housing option that does not restrict animal movement, which is an issue of growing concern for both producers and the general public (Barkema et al. 2015). Additionally, bedded packs are designed for cow comfort (Barberg et al. 2007b; Bewley et al. 2012), and prevalence of lameness, foot, and leg injuries in these systems has been found to be significantly less than tiestall and freestall barns (Barberg et al. 2007b; Lobeck et al. 2011; Burgstaller et al. 2016). The relationship between decreased milk production and lameness is well documented (Warnick et al. 2001; Green et al. 2002), leading to an additional incentive for producers to minimize the prevalence of lameness in a herd. Lastly, manure management and environmental stewardship is a top concern for both dairy producers and the general public (Holly et al. 2018). Anecdotally, the five bedded pack producers enrolled in the study were pleased with their systems of manure management, viewing their used bedding material and manure as a valuable soil amendment and an integral part of their nutrient management plan. Bedded pack systems decrease the amount of liquid manure waste when compared to conventional barns, and the used bedding with manure is more easily composted before use as a soil amendment. As composted bedded pack material is drier before it is spread on fields, it poses less of a risk for run-off into waterways, increases soil infiltration of nutrients, and creates flexibility around timing of manure application to fields (Rushmann). With no obvious disadvantages for udder health or hygiene when properly managed on farms with excellent milking hygiene practices already in place, bedded packs may be an especially good housing option for small, pasture-based farms in the Northeast both now and in the future.

**Conclusion**

The current study is to the authors’ knowledge the first direct comparison of milk quality and udder hygiene on bedded pack farms to both tiestall and freestall herds of similar size and management styles, for a population of entirely small to midsize organic dairy farms. It is also the first to describe udder health and hygiene on bedded packs in the Northeast, which is significant as the performance of these systems can be greatly influenced by climatic factors. Bedded pack systems did not differ significantly in their milk quality, udder health, or hygiene measures when compared to the more commonly used winter housing systems for organic cows in Vermont. Bedded packs can therefore be considered as a viable option for pasture-based herds looking for a more affordable loose-housing system.

**References**

**Figures**

**Tables**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 1. Bulk tank milk aerobic culture outcomes by facility type for 21 Vermont organic dairy herds | | | | | | | | |
|  |  | Count |  |  | Mean | 95% CI | Range | Kruskal-Wallis χ2 |
| *Staph.* spp. (CFU/mL) | | 21 |  |  | 95.5 | 36-155 | 0-665 | 0.9 (df = 2, *P* = 0.62) |
|  | Bedded pack | 5 |  |  | 53 | 10-96 | 0-130 |  |
|  | Tiestall | 10 |  |  | 134.5 | 14-255 | 15-665 |  |
|  | Freestall | 6 |  |  | 65.9 | 28-104 | 5-125 |  |
|  |  |  |  |  |  |  |  |  |
| Non-*ag. Strep.* (CFU/mL) | | 21 |  |  | 156.4 | 42-271 | 10-1250 | 4.6 (df = 2, *P* = 0.10) |
|  | Bedded pack | 5 |  |  | 39 | 17-61 | 10-80 |  |
|  | Tiestall | 10 |  |  | 255.5 | 30-481 | 20-1250 |  |
|  | Freestall | 6 |  |  | 89.2 | 11-167 | 25-260 |  |
|  |  |  | Neg. for *S. aureus* (no. farms) | Pos. for *S. aureus* (no. farms) |  |  |  |  |
| *Staph. aureus* (CFU/mL) | | 21 | 8 | 13 | 43.6 | 14-73 | 0-320 | 3.4 (df = 2, *P* = 0.19) |
|  | Bedded pack | 5 | 3 | 2 | 9 | 0-21 | 0-30 |  |
|  | Tiestall | 10 | 3 | 7 | 63 | 5-121 | 0-320 |  |
|  | Freestall | 6 | 2 | 4 | 40 | 10-70 | 0-100 |  |
|  |  |  |  |  |  |  |  |  |
|  |  |  | Neg. for coliforms(no. farms) | 5 CFU/mL coliforms  (no. farms) | Mean | 95% CI | Range |  |
| Coliforms (CFU/mL) | | 21 | 16 | 5 | 1.2 | 0.3-2.1 | 0-5 | 0.4 (df = 2, *P* = 0.82) |
|  | Bedded pack | 5 | 4 | 1 | 1 | 0-3 | 0-5 |  |
|  | Tiestall | 10 | 7 | 3 | 1.5 | 0.003-3 | 0-5 |  |
|  | Freestall | 6 | 5 | 1 | 0.8 | 0-2.5 | 0-5 |  |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Table 2. Udder health and production outcomes by facility type for 21 Vermont organic dairy herds. | | | | | | |
|  |  |  | Continuous outcomes | | |  |
| Outcome |  | Sample size | Mean | 95% CI | Range |  |
| Bulk tank milk somatic cell count (cells/mL) | | 21 | 144,286 | 121,218-167,353 | 54,000-250,000 | One-way Fisher’s ANOVA: (F(2,18) = [2.137], *P* = 0.15) |
|  | Bedded pack | 5 | 107,600 | 70,275-144,925 | 54,000-160,000 |  |
|  | Tiestall | 10 | 146,400 | 114,136-178,664 | 97,000-250,000 |  |
|  | Freestall | 6 | 171,333 | 126,965-215,702 | 98,000-250,000 |  |
|  |  |  |  |  |  |  |
| Percent of cows with newly elevated SCS (%) | | 19 | 5.7 | 4.2-7.3 | 0-12.3 | One-way Fisher’s ANOVA: (F(2,16) = [0.2128], *P* = 0.81) |
|  | Bedded pack1 | 3 | 7.0 | 2.8-11.2 | 2.9-12.3 |  |
|  | Tiestall | 10 | 5.4 | 3.0-7.8 | 0-10.5 |  |
|  | Freestall | 6 | 5.6 | 3.0-8.3 | 0-9.8 |  |
|  |  |  |  |  |  |  |
| Percent of cows with chronically-elevated SCS (%) | | 19 | 13.6 | 11.2-16.1 | 2.9-23.1 | One-way Fisher’s ANOVA: (F(2,16) = [0.3138], *P* = 0.74) |
|  | Bedded pack1 | 3 | 14.5 | 5.4-23.7 | 2.9-23.1 |  |
|  | Tiestall | 10 | 14.3 | 11.9-16.7 | 7.8-20.8 |  |
|  | Freestall | 6 | 12.0 | 6.7-17.3 | 5.7-23.1 |  |
|  |  |  |  |  |  |  |
| Percent of cows with SCS ≥ 4.0 cells/mL on current test date (%) | | 19 | 24.9 | 21.6-28.3 | 8.6-36.9 | One-way Fisher’s ANOVA: (F(2,16) = [0.1017], *P* = 0.90) |
|  | Bedded pack1 | 3 | 26.0 | 12.6-39.3 | 8.6-36.9 |  |
|  | Tiestall | 10 | 25.4 | 22.1-28.6 | 17.6-32.8 |  |
|  | Freestall | 6 | 23.7 | 16.9-30.5 | 11.6-36.5 |  |
|  |  |  |  |  |  |  |
| Standardized 150-day milk (pounds) | | 18 | 50.0 | 45.7-54.3 | 33.5-68.0 | One-way Fisher’s ANOVA: (F(2,15) = [0.4404], *P* = 0.65) |
|  | Bedded pack2 | 4 | 46.9 | 39.8-53.9 | 38.5-56.3 |  |
|  | Tiestall2 | 8 | 49.4 | 43.1-55.7 | 33.5-68.0 |  |
|  | Freestall | 6 | 53.0 | 43.5-62.5 | 38.7-67.7 |  |
|  |  |  |  |  |  |  |
| Avg. SCS of cows on farm | | 20 | 2.44 | 2.26-2.62 | 1.7-3.3 | One-way Welch’s ANOVA: (F(2,5.7) = [0.02891], *P* = 0.97) |
|  | Bedded pack2 | 4 | 2.38 | 1.84-2.91 | 1.7-3.1 |  |
|  | Tiestall | 10 | 2.45 | 2.31-2.59 | 2.2-2.8 |  |
|  | Freestall | 6 | 2.5 | 2.00-2.93 | 1.9-3.3 |  |
|  |  |  |  |  |  |  |
| 1 DHIA data not available for 2 farms | | | | | |  |
| 2 DHIA data not available for 1 farm | | | | | |  |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 3. Selected results of univariate analysis identifying factors unconditionally associated with udder health and hygiene outcomes at *P* <0.20 for 21 Vermont organic dairy herds | | | | |
| Parameter | | Group (sample size) | Coefficient estimate (SE) | *P-*value |
| Bulk tank milk somatic cell count (cells/mL) | |  |  |  |
|  | Lying surface | Mattress or concrete (n = 13) | 36,000 (23,454) | 0.14 |
|  |  | Deep bedding (n = 8) | Ref. | Ref. |
|  | Depth of bedding in stalls (cm)1 | Tiestalls and freestalls (n = 15) | -5,797 (3,970) | 0.17 |
| Percent cows with newly-elevated SCS (%)2 | |  |  |  |
|  | Glove use | Inconsistent glove use while milking (n = 9) | 2.83% (1.7) | 0.11 |
|  |  | All milkers consistently use gloves (n = 9) | Ref. | Ref. |
|  | Depth of bedding in stalls (cm)1 | Tiestalls and freestalls (n = 15) | -0.62% (0.24) | 0.02 |
| Percent cows with chronically-elevated SCS (%)2 | |  |  |  |
|  | Herds that clip or flame udders one or more times per lactation | Yes (n = 5) | -4.31% (2.9) | 0.16 |
|  |  | No (n = 14) | Ref. | Ref. |
|  | Proportion of cows with udder hygiene scores ≥3 | All herds with available test data (n = 19) | 12.7% (6) | 0.05 |
|  | Average hygiene score | All herds with available test data (n = 19) | 6.39% (3.1) | 0.05 |
| Percent cows with SCS ≥ 4.0 on current test date (%)2 | |  |  |  |
|  | Depth of bedding in stalls (cm)1 | Tiestalls and freestalls (n = 15) | -1.2% (0.42) | 0.01 |
|  | Proportion of cows with udder hygiene scores ≥3 | All herds with available test data (n = 19) | 13.6% (8.5) | 0.13 |
|  | Average hygiene score | All herds with available test data (n = 19) | 7.7% (4.3) | 0.09 |
| Average SCS of cows on farm3 | |  |  |  |
|  | Herds that regularly do parenteral supplementation of dry cows with vit. E and selenium | Regular or occasional supplementation (n = 9) | -0.27 (0.18) | 0.15 |
|  |  | No parenteral supplementation (n = 11) | Ref. | Ref. |
|  | Herds that use any sort of approved organic intramammary product at dry-off | Yes (n = 5) | -0.29 (0.21) | 0.18 |
|  |  | No (n = 15) | Ref. | Ref. |
|  | Depth of bedding in stalls (cm)1 | Tiestalls and freestalls (n = 15) | -0.05 (0.03) | 0.1 |
|  | Proportion of cows with udder hygiene scores ≥3 | All herds with available test data (n = 20) | 0.75 (0.45) | 0.12 |
|  | Average hygiene score | All herds with available test data (n = 20) | 0.39 (0.23) | 0.11 |
| Proportion of cows with udder hygiene scores ≥3 | |  |  |  |
|  | Depth of bedded pack (m) | Bedded pack herds (n = 5) | -0.5 (0.06) | 0.004 |
|  | Lying surface | Mattress or concrete (n = 13) | 0.17 (0.08) | 0.06 |
|  |  | Deep bedding (n = 8) | Ref. | Ref. |
|  | Depth of bedding in stalls (cm)1 | Tiestalls and freestalls (n = 15) | -0.02 (0.02) | 0.13 |
| Average hygiene score | |  |  |  |
|  | Depth of bedded pack (m) | Bedded pack herds (n = 5) | -0.96 (0.15) | 0.008 |
|  | Lying surface | Mattress or concrete (n = 13) | 0.33 (0.16) | 0.06 |
|  |  | Deep bedding (n = 8) | Ref. | Ref. |
|  | Depth of bedding in stalls (cm)1 | Tiestalls and freestalls (n = 15) | -0.06 (0.03) | 0.07 |
| 1 Stall bedding depth for freestalls and tiestalls bedded with wood shavings or sawdust | | | | |
| 2 DHIA data available for n = 19 herds. One herd included in average linear score analyses is seasonal and had no recent test data. | | | | |
| 3 DHIA data available for n = 20 herds. | | | | |

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**Conflict of Interest**

The authors declare no conflicts of interest.

**Author Contributions**

***Comparison of bulk tank milk udder health measures, aerobic culture data, and hygiene scores by facility type***

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**Figure 1.** Bulk tank milk somatic cell count by facility type. The central line of each box represents the median, while the upper and lower lines represent the upper (75th) and lower (25th) quartiles, respectively. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. A one-way ANOVA revealed that there was no difference in bulk tank somatic cell count between any of the three facility types (F(2,18) = [2.137], p = 0.15).

**OR**

**Figure 1.** Bulk tank milk somatic cell count by facility type. Boxplot showing the 25th, 50th (median), and 75th percentiles of bulk tank raw somatic cell count data from 21 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. A one-way Fisher’s ANOVA revealed that there was not a statistically significant difference in bulk tank somatic cell count between any of the three facility types (F(2,18) = [2.137], p = 0.14).

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**Figure 2.** Proportion of cows in a herd with a newly-elevated SCS by facility type, which was defined as the somatic cell score changing from <4.0 to ≥4.0 in the last 2 tests. Boxplots showing the 25th, 50th (median), and 75th percentiles of DHIA data available from 19 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. Outliers are points located beyond the upper and lower whiskers. A one-way Fisher’s ANOVA revealed that there was no difference in proportion of cows with a newly-elevated SCS between any of the three facility types (F(2,16) = [0.2128], p = 0.81).



**Figure 3.** Proportion of cows in a herd with a chronically-elevated SCS by facility type, which was defined as a somatic cell score ≥4.0 on the last 2 tests. Boxplots showing the 25th, 50th (median), and 75th percentiles of DHIA data available from 19 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. A one-way Fisher’s ANOVA revealed that there was no difference in proportion of cows with a chronically-elevated SCS between any of the three facility types (F(2,16) = [0.3138], p = 0.74).



**Figure 4.** Proportion of cows in a herd with elevated SCS by facility type, which was defined as having a linear score ≥4.0 on most recent test day. Boxplots showing the 25th, 50th (median), and 75th percentiles of DHIA data available from 19 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. Outliers are points located beyond the upper and lower whiskers. A one-way Fisher’s ANOVA revealed that there was no difference in proportion of cows with an elevated SCS between any of the three facility types (F(2,16) = [0.1017], p = 0.90).



**Figure 5.** Standardized 150 Day Milk by facility type. Boxplots showing the 25th, 50th (median), and 75th percentiles of DHIA data available from 18 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. Outliers are points located beyond the upper and lower whiskers. A one-way Fisher’s ANOVA revealed that there was no difference in Standardized 150 Day Milk between any of the three facility types (F(2,15) = [0.4404], p = 0.65).



*The variances are not homogenous for this analysis…. Violates an assumption of the regular ANOVA; can’t do Kruskal-Wallis with unequal variance either; so did Welch’s ANOVA (normally distributed, but unequal variances)*

**Figure 6.** Average somatic cell score of cows in a herd by facility type. Boxplots showing the 25th, 50th (median), and 75th percentiles of DHIA data available from 20 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. A Welch’s ANOVA (unequal variances) revealed that there was no difference in average somatic cell score of cows in a herd between any of the three facility types (F(2,5.7) = [0.02891], p = 0.97).



**Figure 7.** Mean hygiene score of cows in a herd by facility type. Boxplots showing the 25th, 50th (median), and 75th percentiles of data from 21 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. A one-way Fisher’s ANOVA revealed that there was not a statistically significant difference in mean hygiene score of cows in a herd between any of the three facility types (F(2,18) = [2.307], p = 0.13).



**Figure 9.** Proportion of cows with dirty udders (udder hygiene score ≥ 3) in a herd by facility type. Boxplots showing the 25th, 50th (median), and 75th percentiles of data from 21 herds. The upper whisker represents the largest observation less than or equal to the 75th quartile plus 1.5 times the interquartile range, while the lower whisker represents the smallest observation greater than or equal to the 25th quartile minus 1.5 times the interquartile range. A one-way Fisher’s ANOVA revealed that there was no difference proportion of cows with dirty udders in a herd between any of the three facility types (F(2,18) = [2.1031], p = 0.15).

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