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Biochar amendment and moisture effects on poultry litter windrow heating performance

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Abstract

Poultry litter is a key factor that effects broiler (meat chicken) production because it can harbor pathogenic bacteria. Windrowing, which is akin to in-house composting can improve poultry litter quality and limit pathogen growth by heating and drying the litter between flocks. Generally, broiler producers manage windrowing to reach high peak temperatures as fast as possible, to reach efficiently pathogen control standards. Biochar, a carbon rich byproduct of biomass energy production, has the potential to improve windrow heating performance by facilitating higher peak temperature and heating rate. In this study, two sources of biochar as litter amendment prior to windrowing, Proton Power biochar and City of Lebanon biochar. Pathogen control standards were 122 °F for 24h or 145°F for 1h, under these standards the pathogens in litter can be destroyed. For the farm scale part of this study, windrow heating performance was monitored in two paired commercial broiler houses, one that received 4000 lbs (1815 kg, dry weight, about 1% of litter in house) versus a control house that did not receive biochar. There was no significant difference in the peak temperatures attained during windrowing in the control and biochar amendment houses. For all treatments, the litter at mid-depth and floor positions of the windrow can reached ≥122 °F for 24h, in the Turn 1 and Turn 2; only the mid-depth position can reached ≥145 °F for 1h at mid-depth, in the Turn1 and Turn 2. The surface position had poor heating performance, did not reach either standards. In the second part of the study, a bench scale experiment was performed to evaluate the effectiveness of two biochars in simulative windrow heating at 1%, 5%, and 10% (dry mass based) amendment rates. In this experiment, the litter moisture was adjusted to 36% during the second

simulative windrow turn. Compared to the non-biochar added control, the biochar again showed no improvement of heating performance. However, the added moisture significantly improved windrow heating in second simulative windrow turn. The bench scale study also illustrated that moisture is a key determinative factor in windrow heating performance.

Key words: poultry litter windrowing, heating performance, biochar application, mixture moisture.

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Chapter 1. Introduction

Antibiotics have been used by the poultry industry to improve broiler (meat chicken) production worldwide since the 1940s. The attitude towards the use of these antibiotic growth promoters (AGPs) for poultry production has changed because of concerns about the rise of antibiotic resistant bacteria. Bacterial antibiotic resistance is a rapidly developing threat worldwide which already reduces treatment options and therapeutic efficacy in human medicine [1, 2]. It is a big challenge for the poultry industry to find alternative ways to control pathogenic bacteria during production while maintaining current feed conversion efficiency.

Poultry litter is a mixture of poultry waste and used beddings, that can harbor pathogenic bacteria. Many poultry producers in Tennessee are transitioning to windrowing litter within the production houses between grow-outs to improve poultry litter quality. Windrowing is a litter management that uses heat released by microorganisms during the degradation of organic material to reduce pathogenic bacteria and dry the litter between flocks (Lavergne et al., 2004). High performance windowing could ameliorate the impact of broiler production without antibiotics.

The research goal is to improve windrow heating performance. Biochar has been used as an amendment in biosoilds composting. Researches had indicated that biochar amendment accelerates microbial activity and increases the temperature during biosoilds composting [3-5]. Therefore, biochar might have the potential to improve windrow heating performance. However, biochar has not been tested as a poultry litter amendment for improved windrow heating performance. The objectives of this research are:

1. Evaluate biochar effects on windrow heating performance
2. Investigate the key factors effect windrow heating performance
3. Improve windrow management

Chapter 2. Literature Review

2.1 Antibiotics in broiler production

2.1.1 Transition of the antibiotic free broiler production

Antibiotics are commonly used during poultry production. Antibiotics likely remodel microbial diversity in the bird's intestine which optimizes feed efficiency [6], and also controls gastrointestinal infections [7, 8]. Antibiotics usage in poultry feed improve food safety by reducing or eliminating certain pathogens in poultry meat [9] and improves the feed conversion ratio [10, 11]. The growth-promoting effects of antibiotics were discovered in the 1940s, when chickens were first fed feed containing antibiotics [12]. Certain types of antibiotics, known as antibiotic growth promoters (AGPs), destroy or inhibit intestinal bacterial growth when administered at a low sub therapeutic dose [13]. Chickens that receive AGPs in feed exhibit higher growth rates than chickens that were not fed feed containing antibiotics. As a result, broiler production changed dramatically from 1955 to 1995: the average market weight of broilers increased nearly 50%, while the time needed to reach market weight and the amount of feed required to produce one pound of broiler meat declined 35% [14, 15]. Although these effects might be in part caused by the improvements in poultry house management and selective breeding. It has been asserted by industry researchers that AGPs remain an essential component in maintaining these increases in productivity, which have markedly decreased cost of chicken meat [16]. Between 1950 and 1960, the use of penicillin increased broiler body weight by ~8.5%, while tetracyclines increased body weight

by ~11% [17]. From 1968 to 1980, broiler body weight increases were found to be 11% for penicillin, 8%–10% for the tetracyclines, and 4%–7% for certain "new" antibiotics [18].

However, studies have shown that the use of AGPs contributes to the contamination of livestock products by selecting for antibiotic resistant pathogens, including *Campylobacter*, *Salmonella*, *Enterococcus* and *E.coli*. Antibiotic resistance has been a concern for several years. Antibiotic resistance is defined as the ability of microorganisms to proliferate in the presence of an antibiotic that generally inhibits or kills microorganisms of the same species [19]. The development of antibiotic resistant pathogens increases risks of human infections by these and other resistant pathogens that cannot be easily treated [20, 21]. Moreover, the residue of antibiotics in food production may have an adverse impact on human health, because bacteria developing resistance in animals may be transmitted to humans or spread their mechanisms of resistance [22].

Many countries now demand that poultry be produced without feed containing antibiotics. The European Union banned the use of antibiotics as growth promoters in animal feed from 2006 [23]. In addition, in January 2017, the United States Food and Drug Administration fully implemented Guidance for Industry #209 and #213 which prohibits the use of all AGPs that are medically important [24].

2.1.2 Potential challenges in removing antibiotics from broiler production

The demand for poultry meat is increasing. The United States has the largest broiler chicken industry in the world, with about 16.5 percent of production exported to other countries in 2017 (National Chicken Council, 2018). A further increase of 2.3 percent to 42.6

billion pounds is predicted for 2018, with the bird weights trending higher [25]. The large demand and scale of broiler production make transitions to production without antibiotics difficult to manage particularly for performance issues such as morbidity, uniformity, and maintaining current feed conversion efficiency after the AGPs ban. The main challenge faced by producers after removing AGPs are undoubtedly related to intestinal health, specifically, the Necrotic enteritis (NE) [26]. Removing antibiotics feed additive is also certain to cause problems in control of other bacterial as well as [27]. It is critical to find alternative to AGPs to control bacteria pathogens in chicken production to prevent disease.

Additionally, the ban of AGPs, will increase cost for production, by lowering feed conversion efficiency. The National Research Council accepted industry estimate and concluded that a 1.76% increase in poultry production costs would arise from the removal of AGPs, resulting in an increased cost to consumers of $2.20 per capita per year. A similar estimate estimated the increase cost for chicken product will be $1.36 to $2.76 per capita [27]. Thus, though the policy to prohibit AGPs is well founded, this action will likely increase cost and thus the environmental impact of poultry production.

2.2 Windrowing

2.2.1 Alternative to antibiotic growth promoters

Pathogens control is the main target to limit the impact of AGPs ban. Most pathogens spread during broiler production through litter, which contains a large and diverse microbial population, up to 10^{10} CFU/g [28], including some pathogens, such as *Staphylococcus*, E. *coli*,

Salmonella, and *Campylobacter* [29]. Poultry litter is a mixture of poultry excreta, spilled feed, feathers, and used bedding on which poultry grow [30]. Litter quality has a significant impact on bird performance. Multiple flocks of birds are commonly reared on the same litter in the modern poultry industry [31]. Poor quality litter has excess moisture and increased disease outbreak. Broilers are sensitive to the in-house environment, including ammonia concentration and bacterial exposure, which are highly dependent upon litter quality [32]. Improving poultry litter quality is the key to improve broiler production.

Windrowing is a litter management technique that use tractors, skid-steer loaders, or specially designed aeration equipment to pulverize and form litter into one or multiple windrows in a poultry house [33]. The windrowing technique uses heat released by microorganisms during the degradation of organic material to reduce pathogenic bacteria and dry the litter between flocks (Lavergne et al., 2004). Through windrow composting, total aerobic bacteria and total anaerobic bacteria are reduced by 10-30% and 60-80%, respectively, and dermatitis and necrotic enteritis are eliminated [33]. This suggests that high performance windowing could control pathogens in broiler litter instead of antibiotics.

2.2.2 Pathogen reduction standards

There is no established pathogen reduction standard for in-house windrowing of broiler litter between flocks. Previous studies generally used two ways to evaluate pathogen reduction, microbial analysis and temperature monitoring. Microbial analysis was mainly focus on the category and concentration of pathogen bacteria in the litter, like E. *coli*, *Salmonella*, and *Campylobacter*. And the common methods were cell counting [29] and DNA

sequencing [34]. Microbial analysis is not practical for commercial poultry producers. Temperature monitoring is commonly used as a practical tool for determining the effectiveness of composting pathogen destruction [35]. Suggested windrow heating standards have mainly been based on the pathogen reduction requirements for biosoilds composting in the US Environmental Protection Agency's (UEPA) 503b Rule. Specifically, when sewage sludge is composted in windrows, the temperature must be maintained ≥ 131°F (55℃) for 15 days, during which time the windrow must be turned a minimum of 5 times [36]. Many studies have confirmed that temperature is critical in the pathogen reduction process. For example, Wilkinson et al. (2011) found a reduction of E. *coli* of more than 99% after 1h at 131°F in laboratory experiment. Macklin et al. (2006, 2008) confirmed a significant decrease of *Salmonella* and other food borne pathogens after 24h at 131°F. Strauch, 1991 summarized a safe zone of pathogen reduction standards, and it suggested certain short time standards of pathogen control temperature, 122°F for 24h or 145°F for 1h.

Windrow turning is one of the composting strategies that control temperature during composting [37]. Different temperature distributions is shown in different depth during windrowing[38]. The temperature of the surface position usually appears to be influenced by the ambient temperature and has low temperature than mid-depth and floor [39]. Studies proved that frequent turning could improve homogeneity of the litter [40, 41]. Therefore, in order to treat all the litter, the windrow must be turned to allow the litter on the outside to be mixed into the core (kill zone) where the temperature is reach pathogen reduce standard (Figure.1).

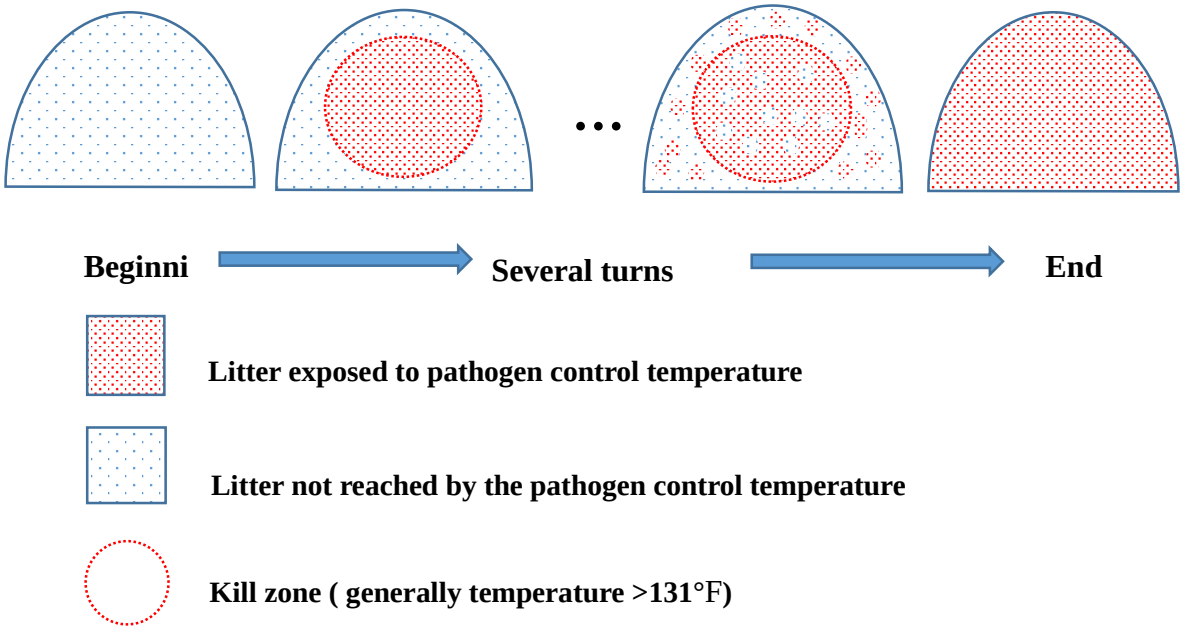


Figure 1.The windrow turning event mechanism.

The purpose of turning the windrows is to assure that all the litter in the windrow is heated to 131°F because the surface temperature is often not hot enough to kill microorganisms.

2.2.3 Challenges of in-house windrowing of broiler litter

The need to attain sufficiently high temperatures for an extended period is critical for in-house windrowing of broiler litter between flocks, if AGPs will no longer be used. To get efficient composting, the moisture content should be maintained between 40% and 60% during the composting process [42]. Thus, for in-house litter windrowing, most litter has a lower moisture content than what is required for optimal heating during windrowing. Another challenges is the relatively short downtimes between broiler flocks, which necessitates a short period (10-14 days) or successful windrowing. [43]. Finally, high performance composting

requires a C/N ratio of approximate 30:1 [44]. Thus, the low C/N ratio of broiler litter may have a negative influence on a successful pathogen reduction and may also contribute to large ammonia emission [45].

2.2.4 Potential methods to improve windrow heating improvement

A variety of windrowing methods have been tested to evaluate the most effective windrowing techniques and the optimal litter conditions. However, few of the tested methods showed an improvement of windrowing performance. For example, to prevent heat dissipation at the surface and improve uniformity of temperature distribution various insulating covers have been recommended. Use of 30-cm finished composting litter as a covering layer significantly improved the heating performance at all locations [46]. A plastic covering is one technique developed by Brazil poultry industry where researchers found that covering the litter with plastic for seven days after watering the litter reduced the presence of *Salmonella* spp. in reused litter [47]. In other studies, a plastic windrow covering did not show advantages. For example, windrows covered with a non-breathable tarp did not reach the recommended temperatures necessary to achieve an effective pathogen reduction [31]. Covering windrowed litter with a PVC plastic sheet had no effect on improving the broiler house environment and instead increased ammonia concentrations [48].

Other researchers have attempted to improve windrow heating performance by adjusting the moisture content of the litter. For example, elevated initial moisture (36 ~ 37 %) ensured adequate pathogen control temperatures were attained. However, increasing the initial

moisture may decrease the workability of litter and results in wetter litter than desired for the next flock [49].

2.3 Biochar

Biochar is a carbon-rich product with high adsorption potential that is derived from the thermal breakdown of plant biomass, organic waste, or even algal biomass under limited oxygen or anaerobic conditions [50]. The International Biochar Initiative (IBI) standardized its definition as "*a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment*" (IBI, 2012).

Biochar has the potential to improve composting (windrowing) performance and reduce ammonia concentrations during broiler production. Compared to the other commonly used amendments, biochar may have significant advantage in enhancing windrow heating performance. It was found that biochar: (1) increased temperature and reduced the time of composting (Table.1), (2) reduced ammonia emissions, (3) changed microbial community structure, (4) enhanced faster decomposition of organic matter, and (5) improved the quality of biochar-blended composts from poultry manure, including chemical composition, water holding capacity, nutrient retention, etc.

Table 1. A summary of the effects of biochar amendment on compost heating performance

NA means not mentioned detail of biochar type in the reference.

Biochar	Compost Ingredients	Biochar Dose	Effect on peak temperature	Reference
NA	Tomato stalk, chicken manure	1%	+13%	Wei et al. 2014
Wood	Poultry manure,	10%	+7%	Jindo, Suto, et al. 2012
Bamboo Wood Manure Coir	sawdust (30% wet weight)		+5~10%	Chen et al. 2017
Pine chips	Poultry litter,	20%		Steiner et al. 2010
NA	poultry manure	5%	Increase temperature	
NA	wheat straw, pig manure		5%	Czekała et al. 2016
Bamboo	wood chip and sawdust	60 kg/ ton	Shorter maintain period	Wang et al. 2013

The all biochar dose were based on wet weight.

The properties of a specific biochar vary according to feedstock and treatment temperature [51, 52]. The biochar made by animal litter and solid waste may have higher inorganic constituents (ash) compared to the biochar from crop and wood biomass [53, 54]. With the same feedstock, the biochar surface area increases when the treatment temperature is increased [55]. Thus, different biochars may have different effects on litter windrowing because of the variable properties.

Chapter 3. Windrow heating study

3.1 Introduction

Litter is a mixture of poultry manure, used bedding (wood shavings), spilled feed, and feathers; litter quality is the key factor that affects broiler health and broiler production efficiency. Broiler producers, farmers that grow meat chicken from chicks to harvest, have begun to practice in-house litter windrowing to improve litter quality. Windrowing is a litter management technique that use tractors, skid-steer loaders, or specially designed aeration equipment to pulverize and form litter into one or multiple windrows in a poultry house (Malone, 2008) During windrowing, pathogenic bacterial populations in broiler litter can be reduced [56-58]. Past research has confirmed that temperature can be used to assess the windrowing performance in regard to pathogen reduction [59-61]. Past research with biosolids which indicated that a temperature of 122°F for 24h or 145°F for 1h, will destroy pathogenic bacteria during composting [62]. However, it is critical for in-house windrowing to obtain high heating performance standards. The challenge of heating performance in farm scale are the relative low moisture content (20-40%), low C/N rate (lower than 25/1), and limited time (less than 15 days).

Biochar was selected as an amendment because past researches indicated that it accelerates microbial activity and increases the temperature during biosoilds composting [3-5]. Therefore, biochar might have the potential to improve windrow heating performance. Biochar has not been tested as a broiler litter amendment to enhance windrow heating performance. A wide range of biochar application rates to compost have been tested, from 5 % to 50% (wet mass

basis). At adequate doses, biochar has been found to increase temperatures and shorten the overall time requirement for adequate heating [3, 4]. Here we present an evaluation of whether biochar amendment can improve in-house windrow heating performance. The research objectives are 1) evaluate biochar effects on windrow heating performance; 2) investigate the key factors effect windrowing

3.2 Materials and Methods

3.2.1 Farm scale windrowing

This research was conducted on a commercial broiler production farm, located in southeast TN, in two paired houses (55ft x 500ft or 17m x 152m). The paired houses received the same chicks from the same hatchery. The broiler houses were divided into Brood and Grow ends. The Brood end was used to rear birds until approximately 7 days of the growout, and received sodium bisulfate acidifier (≈75 lbs/1,000 ft^2, or 34kg/94m^2 of Poultry Litter Treatment; Jones Hamilton, Walbridge, OH) 36 hours prior to the beginning of new flocks. The Grow end was occupied by the flock after the brooding process was completed (after 7 days) and did not receive acidifier.

Windrows were formed after birds were harvested from the production houses using a KMC mode 641D windrowing machine, which was Power takeoff driven by a 95 HP New Hollard TN9S low profile tractor. In each house, 4-5 windrows were typically formed and ran the full length of the production houses. A total of four times of windrowing events were monitored between flocks, each with 2 to 3 turns. The initial windrow was referred as Turn 1, and typically lasted 5 to 7 days, prior to forming new windrow (Turn 2); after an additional 3

to 5 days, the finial windrow (Turn 3) was formed after an additional 3-5 days the windrows were leveled to prepare the house for a new flock.

Table 2 summarizes the house treatments. Two houses received two different biochars (Table 3), Proton Power biochar (PP biochar) and City of Lebanon Biochar (CL biochar). In each biochar treated house, 4,000 lbs biochar (dry mass) was added directly to the top of litter prior to 4 new flocks. Table 3 shows the properties of two biochars used in this study. City of Lebanon biochar (CL biochar) and Proton Power biochar (PP biochar) are used in this research as amendment.

Temperature sensors (Model UA-002-64; Onset Computer Corporation, Bourne, MA) were installed in windrowed litter to record temperature throughout the windrowing process (10 sensors per house). The temperature sensors were set at three depths along the vertical centerline of the windrow profile (Figure 2). In each house, half of the temperature sensors were installed in the Brood, and the remaining five sensors were installed in non-brood end. In each end of the house, 2 sensors were installed within 0-2” of windrow interface with the floor (compacted soil) in two different windrows; 2 sensors were at the mid-depth of windrows; and 1 sensor was installed 0-2” below litter the surface.

Table 2. Windrowing treatments in four test houses

Test House	Biochar type	Dose /lbs	Times of turn in each Growout			
			Growout 1	Growout 2	Growout 3	Growout 4
House 1	Control	0	3	3	2	2
House 2	CL biochar	4,000	3	3	2	2
House 3	PP biochar	4,000	3	3	2	2
House 4	Control	0	3	3	2	2

Growout 1, 2, 3, and 4 presented the four times of windrowing events between flocks.
The dose of biochar added rate was based on the 1% dry mass.
Based on the results in the first two Growouts, the times of turning events reduced at Growout 3 and 4.

Table 3. Properties of City of Lebanon biochar and Proton Power biochar used in this study.

Characteristics	CL biochar	PP biochar
Moisture content (%, wet basis)	54.1 ± 2	9.8 ± 1
Ash content (%, wet basis)	3.0 ± 0.4	7.3 ± 1
TC (%, wet basis)	83.1 ± 5.6	85.3 ± 1.7
TN (%, wet basis)	1.1 ± 0.1	0.8 ± 0.1
BET surface areas (m^2/g)	278.9 ± 0.6	295.1 ± 0.44
PV (cm^3/g)	0.079 ± 0.002	0.083 ± 0.002

TC means total carbon content; TN means total nitrogen content; PV means the pore volume.
BET is a theory that explain the physical adsorption of gas molecules on a solid surface and serves as the basis for an important analysis technique for the measurement of the specific surface area of materials [63].

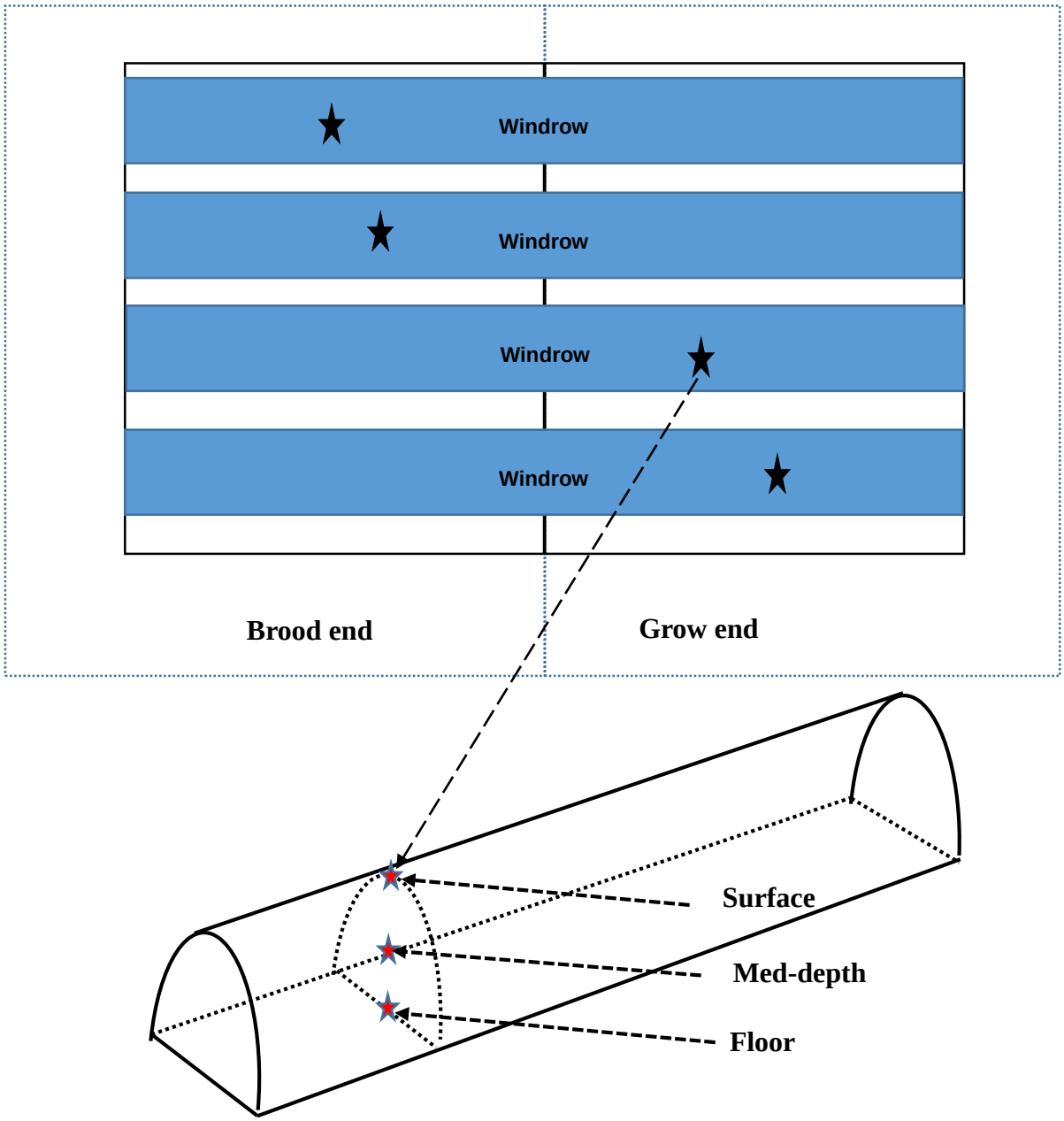


Figure 2. Diagram of temperature sensor installation in the windrows

3.2.2 Bench scale simulative windrowing

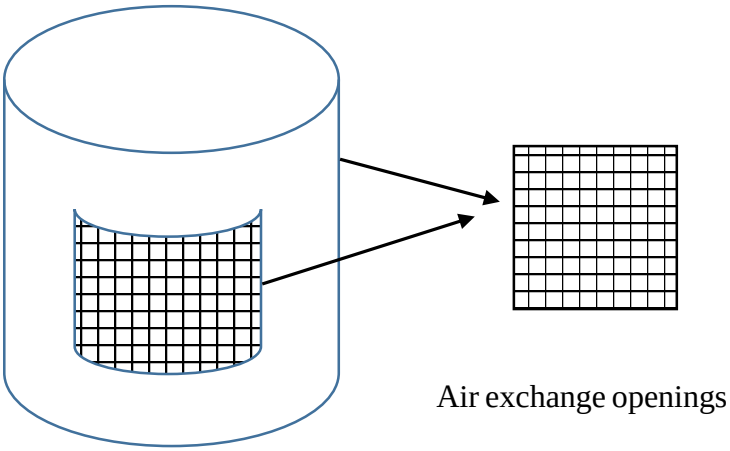
Litter samples were collected from the commercial broiler house in the same farm, immediately after in-house windrowing was initiated so that a completely mixed, uniform litter sample could be collected. Samples were collected using sealed plastic containers to prevent moisture loss prior to performing bench scale simulated windrowing experiments. The initial moisture content of the litter samples were measured by drying litter subsamples for 24h at 221 °F(105°C), both prior to and during bench scale simulative windrowing.

Five-gallon polyethylene buckets were used to simulate windrow core heating (Figure 2). Two 6in x 6in (15cm x 15cm) openings were cut out and screened on opposite sides of bucket to promote oxygen transfer. The size of the air transfer window approximated the surface area to volume ratio of a commercial production house windrow (1.4 ft^2/ft^3 or 6 m^2/m^3), with a width of 12 ft (3.6m) and height of 1.5 ft (0.45m). Fiberglass insulation batts (R19) were placed on the side and top surface of the bucket to simulate litter insulating the core of a windrow. The insulated buckets were filled with litter to a 1ft depth.

Seven treatments were conducted in pairs. The first treatment received no biochar and was taken as control. Subsequent treatments included litter mixed with PP and CL biochar at 1, 5 and 10% (dry weight basis). Two simulative windrow heating events were monitored. After 5 days of simulative windrowing, litter was removed from the bucket and the moisture content was measured. One group of 7 treatments was immediately placed back into the bucket to further monitor heating performance. A second paired group of the 7 treatments had the moisture content adjusted to 36% [49], then the litter was placed back into buckets to further

monitor heating performance.

Temperature was measured in the buckets using duplicate type T thermocouples. Temperature data was collected using a Campbell Scientific data logger specify model 1# every 30 minutes. The temperature sensors were placed 6in (15cm) depth from the top surface of litter (Figure 3).



Simulative windrow core chamber

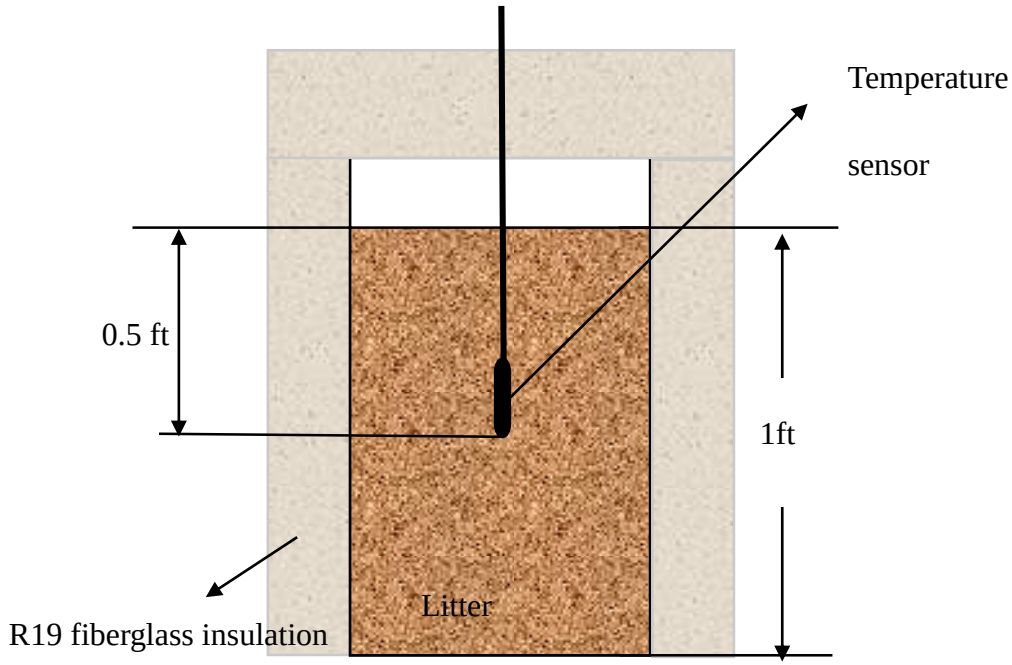


Figure 3. Diagram of container used to simulate litter windrow core heating.

3.3 Results

3.3.1 Peak temperature

In the farm scale study, windrow peak temperature varied significantly at the three depths (Kruskal-Wallis test, $p < 0.001$) (Figure 4). The peak temperature data did not follow normal distribution, therefore we used the non-parametric method to compare the median of peak temperature data. However, there was no significant difference in windrow peak temperature between the Brood and Grow ends of the production houses. A Duncan's Multiple Comparison test indicated that the peak temperatures at mid-depth (128 ± 26℉) was significant higher than the floor peak temperatures (119 ± 21℉). The surface had the poorest heating performance (103 ± 21℉), with the lowest peak temperature compared to the floor and mid-depth. The median of peak temperatures at mid-depth (median 145℉) and floor (median 128℉) exceeded one recommended threshold (122℉) for pathogen control. However, only the mid-depth position exceeded a higher threshold for pathogen control (145 ℉). The peak surface temperatures (median 108℉) rarely exceeded 122℉. These findings indicate the exterior litter appears to insulate the interior litter, allowing the core location to reach higher peak temperature. Conversely, the floor peak temperature data indicated heat loss occurred to the ground by conduction, while the surface peak temperature data indicated conductive heat loss occurred to the house atmosphere. The surface temperature data in particular confirms that at least two windrow turns are needed to assure that the exposed litter will be turned into a new windrow interior and thus exposed to pathogen control temperature.

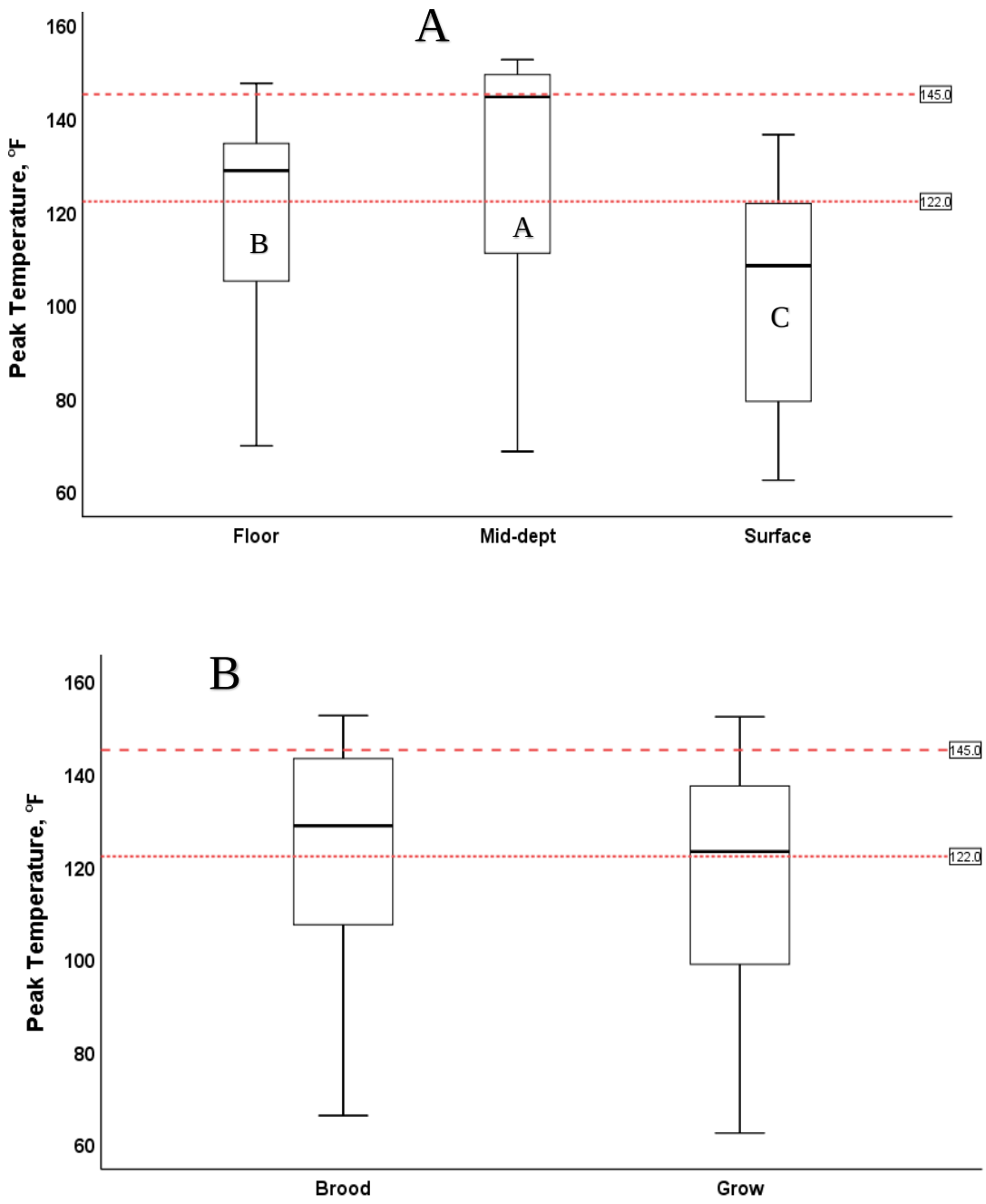


Figure 4. Boxplots of windrow peak temperature at different positions within the windrow (A) and windrow in the Brood and Grow ends of the houses (B).

Data with the different letter (A, B, C) are significantly different (Duncan's Multiple Comparisons, N=350, α=0.05).The two reference line show the temperature threshold of 122 ℉and 145℉.

Windrow peak temperature declined after the litter windrows were turned (Kruskal-Wallis test, $p < 0.001$) (Figure 5). At all three positions (mid-depth, floor, and surface), Turn 1 (142 ± 9℉) had higher peak temperature than Turn 2 (125 ± 15℉); Turn 2 had higher peak temperature than Turn 3 (87 ± 20℉) (Duncan's Multiple Comparisons, $p < 0.05$). The median of peak temperatures of both mid-depth and floor can reach and exceed 122℉ in Turn 1 and Turn 2. However, the median peak temperatures in the Turn 3 did not exceed 122 ℉.

3.3.2 Biochar effects

Windrow peak temperature did not vary across the four treatment houses and across the four growouts (Figure 6) Kruskal-Wallis test, $p = 0.726$. Thus, in this study biochar did not improve the peak temperature during windrowing. The lack of a treatment effect may because of the biochar application (1% dry basis) in this study was too low to improve windrowing. It indicated that maybe need increase the amount of biochar amendment to evaluate the improvement of biochar to windrowing heating performance in farm scale study

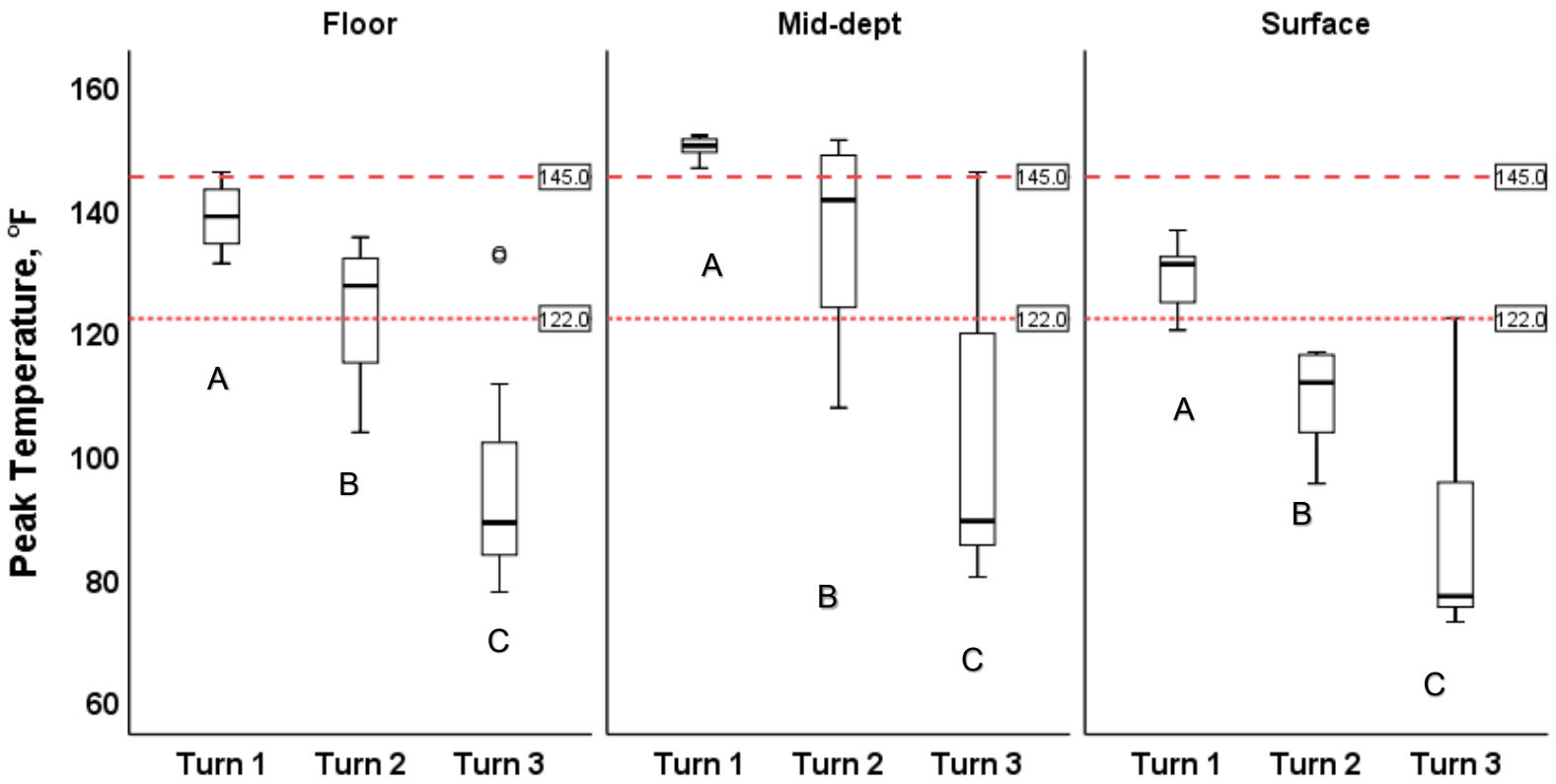


Figure 5. Boxplots of windrow peak temperature across turning events at three positions of Growout 1.

In each position, the peak temperature are different (Duncan's Multiple Comparisons). The result of Growout 2-4 were same with Growout 1.

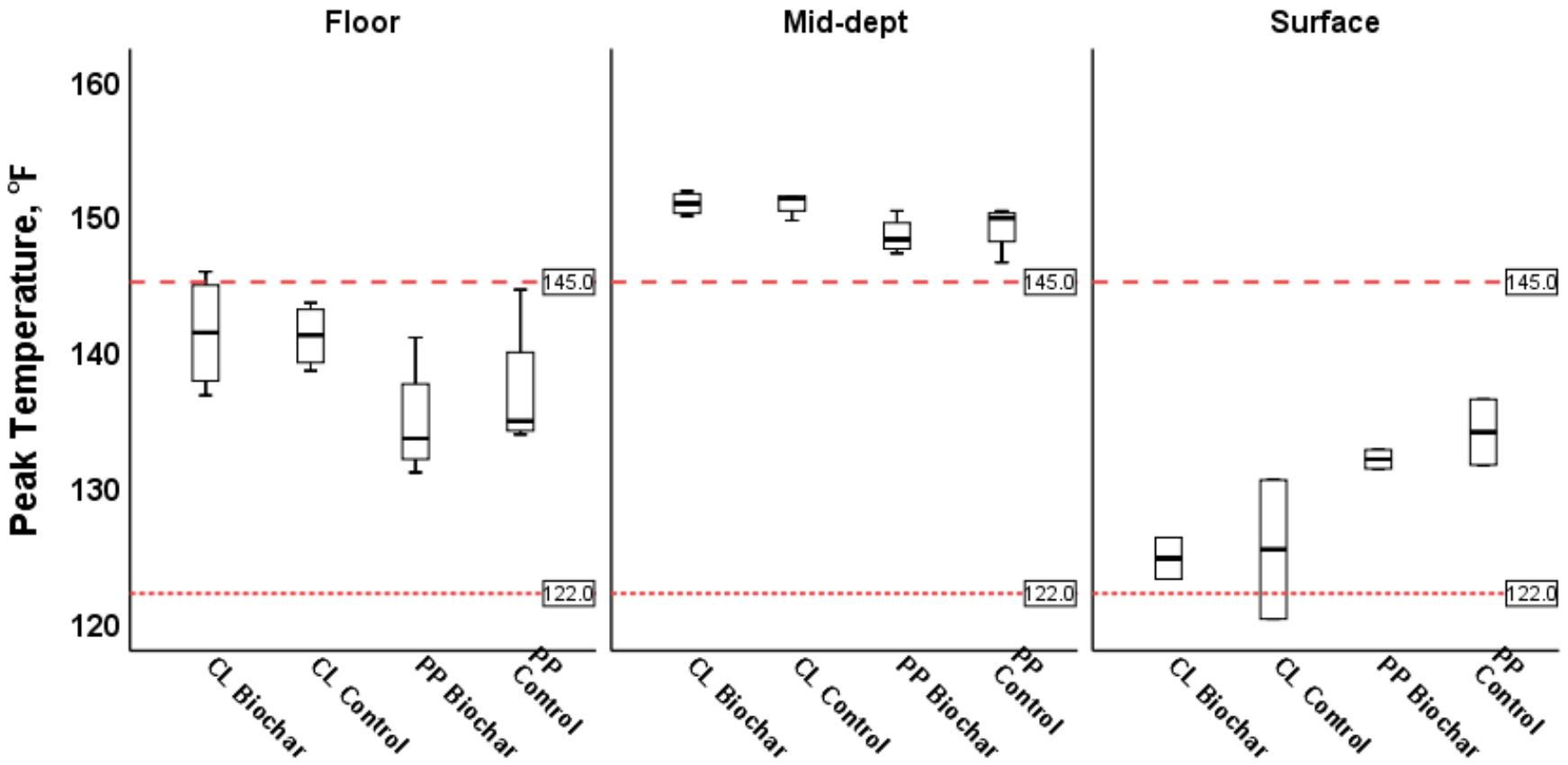


Figure 6. Boxplots of windrow peak temperature between treatments at three positions in the Turn 1 of Growout 1.

There is no difference between the median of the peak temperature the four treatments (Kruskal-Wallis test, p = 0.726). The result was same with other windrow events.

3.3.3 Moisture and windrow size effects

A correlation analysis was completed to determine whether heating performance at the farm scale was related to litter moisture and windrow size among other factors (Table 4). The strength of correlations was defined with the |r| value. When |r| was 0.1~ 0.29, the two variables show low strength correlation. When |r| was 0.30~ 0.49, the two variables show medium strength medium strength correlation. When |r| was 0.50 ~ 1, the two variables strong correlation (Pallant, 2013). Results in Table 4 shows that the peak temperature was highly correlated to the turn event, and moisture content (t-test, $p < 0.01$). The litter moisture content in litter was highly correlated to the turn events (coefficient: -0.679, $p < 0.01$) Windrow depth showed a small correlation to heating performance, but had a significant small correlation to peak temperature (coefficient: 0.256, $p = 0.016$).

A multiple regression analysis of peak temperature was conducted using the best subset method with SPSS V25. Moisture content and depth were used as independent variables. Through the correlation analysis, these two detected factors show the most significant effects on peak temperature. Using a linear multiple regression model to fit the peak temperature at floor and mid-depth with moisture content and windrow depth, the two models can explain 48~50% of the increase of peak temperature (R^2= 0.50, 0.48, $p < 0.001$) (Table 4). The regression model also estimate the parameter coefficients of moisture and windrow depth, as well as corresponding standard errors, t-statistics, and p-levels (Table 5). The estimated regression model at Floor is:

Peak Temperature = 21.44 + 2.193*Moisture Content (%) + 1.864*Depth (in)

(1)

Adjusted R^2=0.50.

Table 4. Pearson correlation analysis of peak temperature and variables in the study

	Treatment	Turn	Moisture content	Depth	Peak temperature
Treatment		0.020	-0.234	-0.012	-0.151
Turn	0.020		-0.679**	-0.075	**-0.648****
Moisture content	-0.234	-0.679**		0.043	**0.582***
Depth	-0.012	-0.075	0.043		**0.256***
Peak temperature	-0.151	-0.648**	0.582*	0.256*	

*. Correlation is significant at the 0.05 level (2 - tailed); **. Correlation is significant at the 0.01 level (2 - tailed), N = 350, $\alpha = 0.05$

The estimated regression model at Floor is:

Peak Temperature = 7.45 + 2.622*Moisture Content (%) + 5.083*Depth (in) (2)

Adjusted R^2=0.48.

Parameters in equation (1) and (2) have positive values, indicating the increase in the average peak temperature with moisture content and windrow depth at floor and mid-depth. At both the floor and mid-depth positions, peak temperature increased significantly as the windrow depth increased. Larger (deeper) windrows tended to produce higher peak temperatures, and the amount of compost exposed to high temperatures would also increase. Peak temperature declined as the moisture content decreased.

3.3.4 Pathogen reduction standard

Temperatures of ≥122℉lasting for 24h or ≥145℉lasting for 1h were used as standards to assess the adequacy of windrow heating for pathogen reduction [62]. For both mid-depth and floor, when the temperature reached 122℉, 88% of temperature data at floor met temperatures≥122℉for 24h in Turn 1, and 47% of temperature data met the standard in Turn 2. 92% of peak temperature data at mid-depth can met temperatures≥122℉for 24h in Turn 1, and 58% of temperature data met in Turn 2 (Figure 7). Only the mid-depth temperature data can reach 145℉ and maintain the temperature for 1hrs in Turn 1 and Turn 2 (Figure 8). 92% of peak temperature data at mid-depth can met temperature≥145℉ last for 1hr in Turn 1, and 33% of temperature data met in Turn 2. Less than 5% of the temperature data at floor met the temperatures≥145℉for 1hr in the Turn 1, and none of temperature data at floor reached 145 ℉in Turn 2.

Table 5. The analysis of variance of a linear multiple regression at floor and mid-depth

Model		Sum of Squares	df	Mean Square	F	p-value
Floor	Regression	29835.111	2	14917.6	67.33	0.000**
	Residual	29467.355	133	221.559		
	Total	59302.466	135			
Mid-depth	Regression	43087.848	2	21543.9	62.948	0.000**
	Residual	45177.165	132	342.251		
	Total	88265.013	134			

**Coefficient is significant at the 0.01 level (2 - tailed)

Table 6. Parameter estimates of the two variables linear regression model at floor and mid-depth

Model		Coefficients		t	p-value
		Beta	Std. Error		
Floor	(Constant)	21.444	8.933	2.401	0.018
	Moisture	2.193	0.233	9.405	0.000**
	Depth	1.864	0.504	3.699	0.000**
Mid-depth	(Constant)	7.449	11.204	0.665	0.507
	Moisture	2.622	0.289	9.085	0.000**
	Depth	5.083	1.173	4.332	0.000**

** Coefficient is significant at the 0.01 level (2 - tailed)

Compared the total time cost to meet the goal (time to reach the temperature threshold plus the required time duration) for the two pathogen control temperature in Turn 1 and 2. A Nonparametric test was used compare the medians of time duration to reach temperature ≥122℉ for 24h at floor (Figure 9). At floor Turn 1 took 68h (median of temperature data) to reach the goal, while Turn 2 was significant shorter than in Turn 1 with 59h ($p = 0.008$). At mid-depth, the median time to meet the goal of 122℉were 42h in Turn 1 and 33h in Turn 2; the median time to meet the goal of 145℉were 36h in Turn 1 and 19h in Turn 2. The results also showed that the time duration to reach the temperature thresholds in Turn 2 was shorter then in Turn 1 ($p = 0.043$, $p<0.001$). It indicates that temperature before turning can affect the time duration to reach the temperature standard in next turn. The higher temperature of the windrow before taking a turn, less time cost to reach the pathogen reduction temperature in next turn.

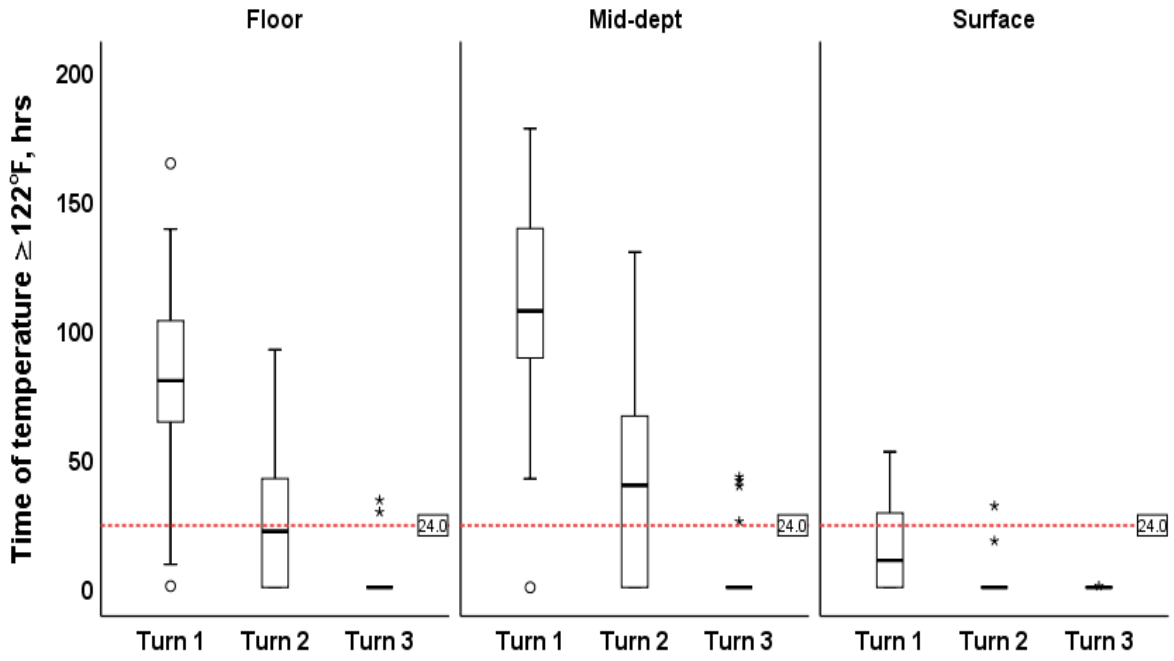


Figure 7. Boxplot of the time duration of temperature ≥122°F in three depths.

The dashed reference line shows the required time duration of pathogen reduction (1h).

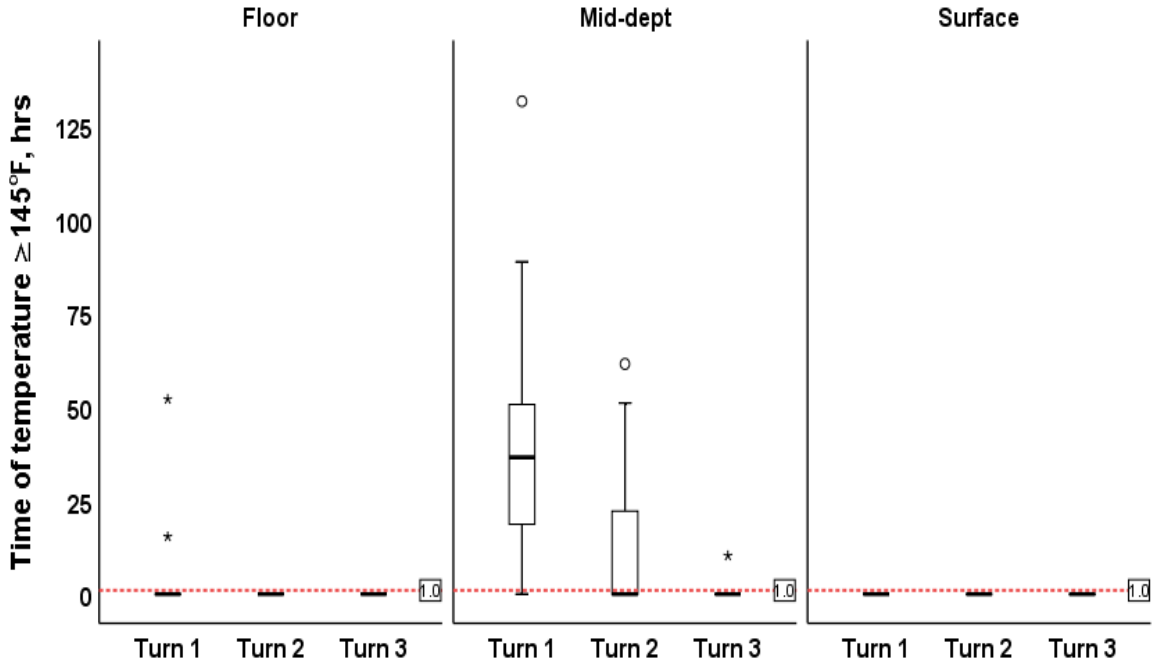
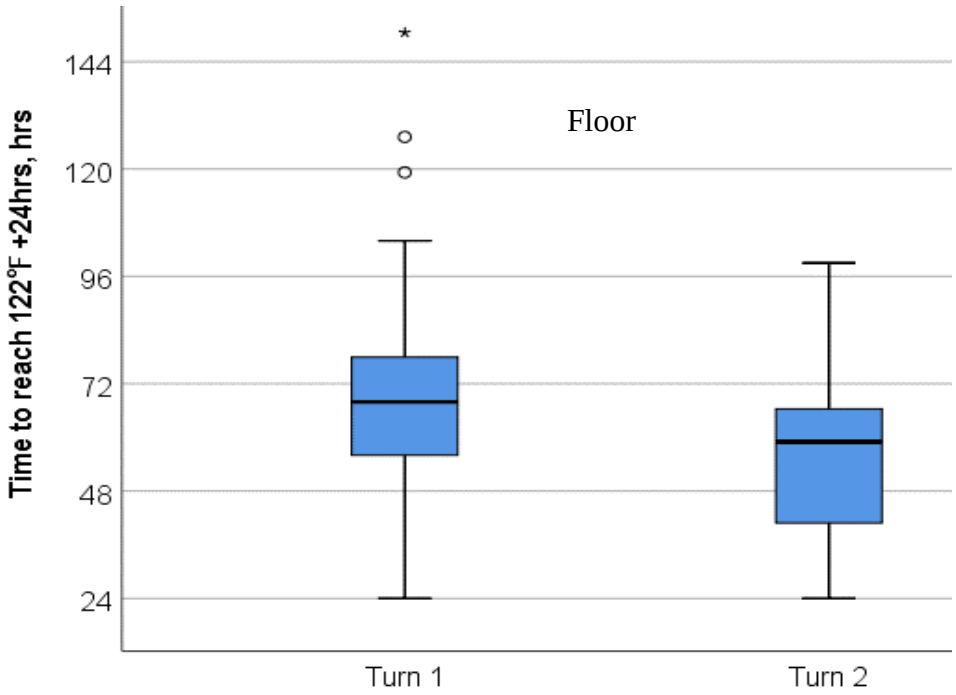


Figure 8. Boxplot of the time duration of temperature ≥145°F in three depths.

The dashed reference line shows the required time duration of pathogen reduction (24h).



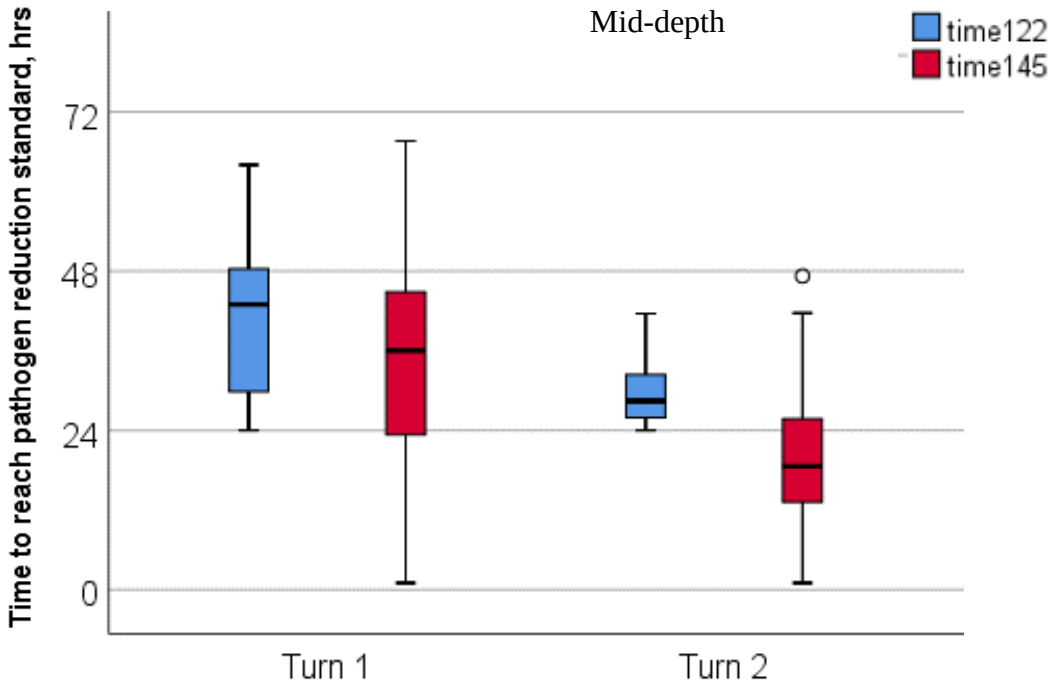


Figure 9. Boxplot of the time duration to reach the pathogen reduction standard.

The time 122 is the time to reach 122°F+24h; The time145 is the time to reach 145°F+1h. Paired sample t-test to compare the time duration.

3.3.5 Biochar effect on simulative windrowing

In the bench scale study, both CL biochar and PP biochar treated mixture show significant effects on peak temperature and heating rate during the simulative windrowing (Tukey HSD, $p < 0.001$). Both biochar treatments did not improve the heating performance (Table 7). The control with no biochar amendment had a higher peak temperature (143℉) and higher fastest heating rate (6℉/h). Both biochars at the 1% amendment rate show no significant difference of the peak temperature with control (~145℉), while the fastest heating rate was 0.7~0.9℉/h lower than control treatment. All three treatments reached 122℉in 7~7.5h and maintain the temperature ≥122°F for more than 50h.

Higher biochar amendment rates (5% and 10%) showed negative effects on heating performance. The peak temperature of 5% and 10% biochar treatments was significantly lower than the peak temperature of control (Tukey HSD, $p < 0.001$), except for the CL biochar 10% treatment. It also took longer for these higher amendment treatments to reach 122°F (8~16.5h) and maintain a shorter period time to temperature ≥122°F (22.5~46.5h).

The CL biochar showed different heating performance with the PP biochar, especially at the 5% and 10% amendment rates. The main difference between these two biochar is the moisture content. CL biochar has much higher moisture content than PP biochar (Table 3). This indicates that the moisture content of biochar itself might have effect on heating performance.

Table 7. Parameters in first simulative windrow heating turn

Treatment	Peak Temperature,℉	Time Temperature ≥ 122℉, h	Time to 122 ℉, h	Initial MC,% wet basis	Final MC,% wet basis	Fastest heating rate, ℉/h
PP biochar 10%	131 ±0.4[c]	27.5	15.5	32.5	27	2.0[d]
PP biochar 5%	128 ±0.03[d]	22.5	16.5	31.5	27	2.5[d]
PP biochar 1%	145 ±0.1[a]	53	7	32	31	5.3[b]
Control	143 ±1.0[ab]	59.5	7.5	32	32	6.2[a]
CL biochar 10%	140 ±0.1[b]	46.5	14	32	27	4.0[c]
CL biochar 5%	132 ±0.3[c]	31.5	8.5	32	30	4.0[c]
CL biochar 1%	145±0.05[a]	52.5	7.5	31.5	30	5.5[b]

The standard error of time Temperature ≥ 122℉ and Time to 122℉ are ± 0.5hr. The one-way ANOVA test the maximum data of 4 temperature sensors of each treatment.

3.3.6 Moisture addition to second windrow turn

For turn 2, the moisture content of half the buckets was adjusted to 36% moisture. This induced an effect on the heating performance (Wilcoxon signed rank test, $p < 0.01$). All of the buckets with moisture addition, except for the CL biochar 10%, had much higher peak temperature and heating rate than the buckets that did not have moisture added (Table 8). For those samples with moisture added, the control treatment showed the best heating performance, higher peak temperature (143℉), reaching 122℉ within 18hrs and maintaining it for 39.5h. For PP biochar, when the moisture content adjusted to 36%, 10% amendment rate PP biochar showed higher peak temperature (142℉) than 5% and 1% amendment rates (139℉and 111℉), and a close time to reach 122℉and period time of temperature ≥122℉with control (20h and 35.5h). For CL biochar, when the moisture content adjusted to 36%, CL 1% and 5% amendment rates treatment took longer to reach 122℉(23.5~40.5h) and maintain it with shorter period (28.5~33.5h). The results show that both CL and PP biochar show no improvement of heating performance either with or without water adjustments in second simulative windrowing. Additional moisture added into litter mixture improve the heating performance, both peak temperature and heating rate (Figure 10 and 11). In contrast to treatments water added, the CL biochar 10% treatment stopped heating after moisture content was adjusted higher. However, this sample generated sulfurous odors indicating anaerobic conditions.

Table 8. Parameters in second simulative windrow heating turn

Treatment	Peak Temperature , ℉	Time to 122℉, h	Time Temperature ≥ 122℉ ,h	Initial MC ,% wet basis	Final MC ,% wet basis	Fastest heating rate, ℉ /h
PP biochar 10%	142	20.5	35.5	36	34	4.3
	95	-	-	27	26	0.7
PP biochar 5%	139	17	34.5	36	35	4.4
	98	-	-	27	27	0.8
PP biochar 1%	111	-	-	36	34	1.4
	81	-	-	31	30	0.5
Control	143	17.5	39.5	36	35	4.0
	108	-	-	32	30	1.0
CL biochar 10%	88	-	-	36	35	0.6
	145	22.5	38	27	26	5.0
CL biochar 5%	133	23.5	28.5	36	34	3.0
	86	-	-	30	29	0.3
CL biochar 1%	134	40.5	33.5	36	35	2.7
	85 ± 0.0	-	-	30	29	0.4

The standard error of time Temperature ≥ 122℉ and Time to 122℉ are ± 0.5h.

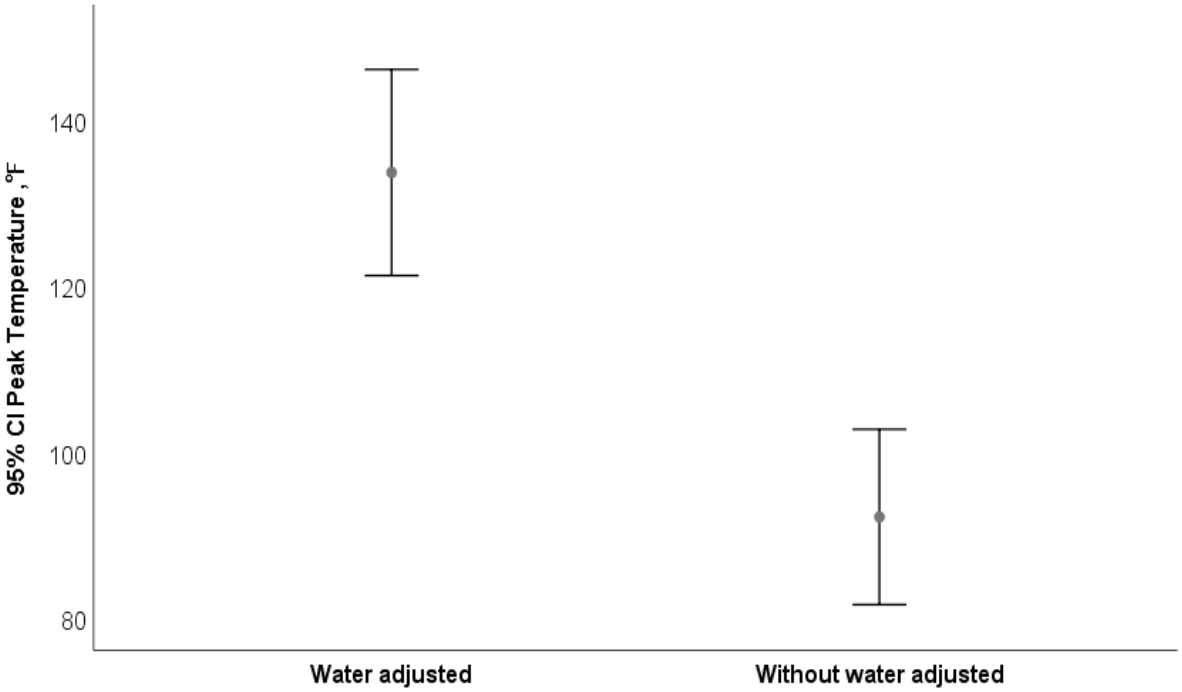


Figure 10. Error bar (standard error) of the peak temperature of the group with and without water adjustment, except the CL biochar 10% treatment.

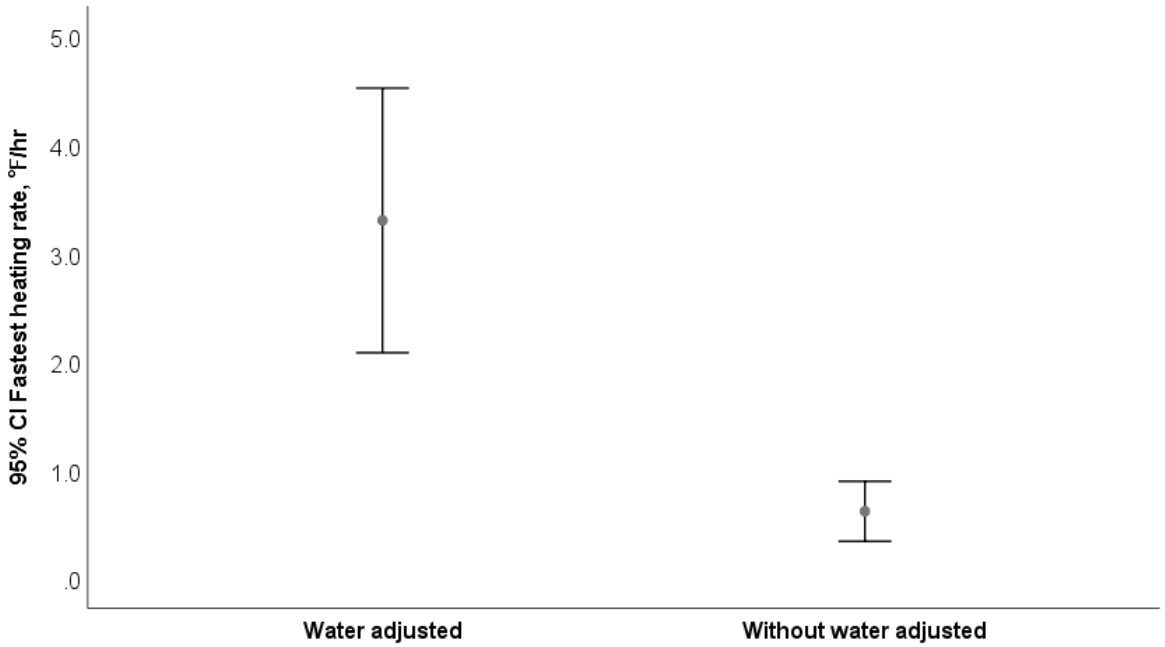


Figure 11. Error bar (standard error) of the heating rate of the group with and without water adjustment, except the CL biochar 10% treatment.

3.4 Discussion

This study did not indicate that biochar improves windrow heating performance both in farm and bench scale study. This finding is inconsistent with previous studies which have indicated that biochar can improve compost heating performance [5, 64]. However, these pervious studies did not evaluate biochar effectiveness for litter windrowing. Wei et al., 2014, showed that 1% biochar application increased 13% of peak temperature. In their study, they mixed chicken manure and tomato stalk, and adjusted the C/N ratio of to around 25/1; the water content to 60%. Jindo et al., 2011, showed that 10% wood biochar application raised the temperature with 7%. In their study, they mixed the poultry litter with apple pomace, rice straw, and rice bran to adjust the C/N ratio, and maintained the moisture content at around 60% by adding water. Compare to composting research, the in-house windrowing does not adjust the C/N ratio and moisture content before windrowing. Biochar failed to improve the windrow heating performance may because of the limited condition of litter for microbial organisms. Generally, for microbial organisms need C/N ratio about 25:1 to 30:1 and moisture content about 50-60% in composting [65-67]. Biochar improved the heating performance mainly by offering a habitat for microbial organisms [64]. When the windrow condition limits the activities of microbes, the effect of biochar might also be limited. The initial moisture content in our study was about 30~40 %, which lower than composting study, which may limit microbial activities. It indicated that biochar did not work effectively when the moisture content of windrow mixture is low.

Moisture is a key factor that influences windrow heating performance, especially the peak temperature. A higher moisture content was correlated to higher peak temperature both in farm and bench study. The peak temperature decreased across the turning events, largely due to the moisture content reduction. During windrowing, moisture level would reduce due to evaporation and the self-heating during the thermophilic phase, especially at the surface [68]. Water loss through the drying process significantly lowers the peak composting temperature which may increase the potential of the survival bacterial pathogen survival [69].

Peak temperature increased, at the mid-depth and floor positions with the windrow depth. The result indicate the large windrow size can improve heating performance. A previous study showed that windrow size directly affects the amount of compost exposed to high temperatures, and the large windrows have higher temperatures as compared to smaller windrows [70]. The large windrows have a lower surface area to volume ratio, which relates to less heat loss and higher composting temperature [71]. With the same width and length, the temperature in larger windrows (6.5ft or 2m height) were significantly two times higher ($p < 0.05$) than those observed in smaller windrows (3.3ft or 1m height) [70].

Litter windrowing should be effective, safe and fast. The standard of ≥122℉for 24h and ≥145℉for 1h [62] takes less time compared a previously used standard of 131℉for 3-5 days [49]. There has been little research using 122℉for 24h or ≥145℉for 1hr as temperature standard in composting. A broiler litter windrow study used 122℉for 24h, and 131℉for 4h as temperature goal and compared the spatially temperature[36]. This study showed the results that when core area reach 122℉for 24h, 81±4% of the windrow area can reach 122℉,

while when the core reach 131℉for 4h, only 38 ±11% of the windrow area can reach 131℉. This shows that relative low temperature standard can easier to reach at most area of the windrow. These similar results were obtained in our farm scale study. The145℉for 1h took less time to achieve only at the mid-depth area position. The 122℉for 24h standard was met in the most area of windrow, and may be a better indicator of the process of the pathogen reduction. Based on the standard of 122℉last for 24h, the farmers are suggested to turn the windrow every 3 days (Figure 9).

Chapter 4. Conclusions and recommendations

1. Biochar application did not improve windrow heating performance when added to broiler litter at 1%, 5%, or 10% rate.
2. Moisture content is critical for windrow heating. Higher initial moisture content yielded better heating performance. This suggests that broiler producers should windrow immediately after flocks are harvested, when the moisture content in litter is the highest.
3. Larger windrows provide better windrow heating performance. Broiler producers should form larger windrows for better heating, and this will prevent premature drying that occurs in small windrows.
4. Based on the pathogen reduction standard of 122℉lasting for 24h, broiler producers are suggested to turn the windrow every 3 days, 2-3 times.

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Vita

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