EVALUATION OF COMMERCIALLY AVAILABLE MOISTURE-SENSING DEVICES TO MONITOR FEATHER WETNESS

A Thesis Submitted to the College of

Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of Master of Science

In the Department of Animal and Poultry Science

University of Saskatchewan

Saskatoon

By

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OVERALL ABSTRACT

The ability to detect moisture in broiler feathers for five moisture-sensing devices using varying techniques, an infrared (IR) camera, and one type of moisture-sensitive paper was evaluated in two experiments; using artificial feather beds in laboratory settings and in field conditions using live birds. In the first experiment (lab testing-phase I), seven levels of moisture were applied once per day to the swatches with four different feather densities to account for moisture variation and feather density present in commercial barn conditions. True moisture of the feathers was determined gravimetrically on a daily basis. Using the five devices, 20 readings each were acquired from each of the swatches. The average temperatures of a selected area from images captured using an IR camera along with average device readings were compared with the true moisture content. Moisture-sensitive paper images were analyzed in Photoshop and Matlab prior to statistical analysis. Data from all devices, the IR camera, and moisture-sensitive paper were analyzed using SAS Procedure GLM to define relationships between the true moisture content and the readings. The devices were analyzed based on their accuracy, consistency and sensitivity using adjusted-R^2, standard error, and regression slope, respectively. The data from all devices and techniques were significantly correlated with feather swatch moisture content ($P \leq 0.05$). Results from the first experiment suggested potential to measure feather moisture by several of the tested devices. While feather density presented as a challenge during this experiment, it was not considered as a significant issue when evaluating the devices. The “Hay” and “Construction 1” sensors showed the most promise in detecting feather moisture and were selected for further testing using live birds. The two devices had relatively higher accuracy, consistency, and sensitivity compared to other devices and techniques.

The second experiment (field testing – phase II) evaluated the two selected devices (Hay and Construction 1 sensors) in various commercial broiler settings. Device readings were acquired from the back, wing, and breast feathers. A sample of back feathers from each bird was collected to determine the true moisture. Statistical analyses of data were the same as in experiment 1. Although the initial study, conducted within a lab setting, denoted a significant relationship between true moisture content and device readings, testing within the field environments showed the devices to perform poorly. Readings from both devices and for all the locations tested demonstrated a lack of sensitivity, accuracy, and consistency for measuring moisture in feathers of live birds.

Key Words: moisture-sensing devices, wetness, broilers, feathers, transportation

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Trever Crowe, for sharing his ideas and wisdom, as well as for having so much patience while I attempted to understand simple engineering ways. I would also like to thank Dr. Hank Classen and Dr. Karen Schwean-Lardner for being on my committee and answering continuous questions I had throughout my program. I would like to extend my gratitude to Dr. Tim Mutsvangwa, my graduate chair, and Dr. Charles Maule, my external examiner, for giving their time and knowledge. I would like to acknowledge Dr. Fiona Buchanan and Dr. Bernard Laarveld for stepping in as the graduate chair during my permission to write and defense meetings, respectively.

I am grateful to staff at the Poultry Centre and Jason Bartoshewski from Sofina Foods/Lilydale (Wynyard) for the help during the data collection. Special thanks to Megan Strawford and Dustin Eichhorn for helping out with my research, planning, data collection, and making my life easier in general.

Finally I would like to thank my friends and family who listened to my troubles and woes and offered me words of encouragement. It is because of everyone's help and support that I am here today, so thank you.

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1.0 INTRODUCTION

Transportation is almost always a necessity in broiler production. During transit, broilers are subjected to a variety of stressors that may eventually lead to mortality. Mortality in transit is an observable indicator of poor welfare conditions to which birds are exposed. There is substantial interest in improving welfare during broiler transportation and reducing the number of birds arriving dead (DOAs) to the processing plant (Thomson et al., 2011). A majority of existing research has suggested that most of the birds that are dead upon arrival at the processing plant are a result of transportation stressors. There have been few studies that recognize on-farm conditions, separate from transit conditions, which may also contribute to DOAs. The presence of moisture on the birds or bird feathers is such a condition that may be detrimental to birds' health and welfare, especially in combination with other transportation stressors. Birds may get wet as a result of moisture accumulation inside the barn due to inadequate ventilation or due to other factors such as high ambient humidity and leaky drinkers. A number of organizations have established recommendations against the transportation of wet birds (Alberta Farm Animal Care Association, 2007; Canadian Agri-Food Research Council, 2003; European Food Safety Authority Panel on Animal Health and Welfare, 2011). Wet birds are particularly an issue in Western Canada where the winter temperatures may drop as low as -40°C. However, as there is ambiguity surrounding the term 'wet' and a lack of an ability to measure feather wetness, transportation of wet birds still occurs.

While there are multiple moisture-sensing devices available commercially, to our knowledge there is not one specifically for measuring moisture in live bird feathers. However, as most sensors use techniques associated with dielectric parameters to obtain moisture readings (capacitance, conductance, resistance, or the change in dielectric constant) (Wernecke and Wernecke, 2014), in theory, it is possible to use these devices to measure feather wetness.

This thesis focuses on evaluating the ability of a number of commercially available moisture-sensing devices to monitor feather wetness; first in laboratory settings using artificial feather beds, then in field conditions using live birds.

2.0 LITERATURE REVIEW: IMPACT OF WET FEATHERS ON BROILER PRODUCTION

2.1 Introduction

The global broiler industry has experienced great advances with the assistance of emerging technology and knowledge. While attempting to improve broiler production and optimize profit, there are certain negative aspects that are often overlooked. Producers can face allegations of providing poor welfare conditions for broilers in order to maximize their income. Broilers have been genetically selected for fast growth and regularly face repercussions of such selection. For example, rapidly growing broilers have been known to have more skeletal and cardiac disorders, and skin lesions than slower growing chickens (Duncan, 2001; Bessei, 2006).

Consumers are becoming more informed and curious as to where their food originates and demand high-quality treatment for animals. Welfare conditions not only affect the animal, but in the long run may also impact profitability of animal production as well. Therefore, it is important to ensure good welfare conditions that will not only benefit the animal but also allow profitability. In order to get such results, first the management practices that influence the welfare of the birds must be understood. Five freedoms described in the Brambell report (1965) have been used to set minimum welfare standards for production animals by the Farm Animal Welfare Council (2011).

The impact of poor welfare conditions on broilers has been studied for decades. It is relatively well researched with regards to bird handling and transportation conditions. However, very few researchers, if any, have looked into the effects of wet feathers prior to transportation on profit and animal welfare. Wet birds are especially an issue in cold climates when producers reduce barn ventilation to decrease production costs, resulting in moisture accumulation and absorption by the feathers. Although the transportation of wet birds is not recommended by various animal-health, welfare and research-based organizations (Alberta Farm Animal Care Association, 2007; Canadian Agri-Food Research Council, 2003; European Food Safety Authority Panel on Animal Health and Welfare, 2011), due to the ambiguity surrounding the term “wet”, wet birds are still being transported. The poultry industry is advancing at a fast pace, experiencing much improvement. However, there is still a lot more that can be done to improve quality of broiler life while maintaining profit. This literature review will discuss broiler welfare associated with transportation, wet birds, and potential techniques available to assess feather moisture.

2.2 Broiler welfare

Animal productivity, profit, and welfare are intricately connected to each other. While attempting to maximize profit and productivity, it is possible to compromise welfare conditions (Stricklin, 2011). Commercial broiler production is no exception to this issue. The broiler industry production (number of birds) has increased considerably and it is being conducted under highly intensified conditions (Mench, 2011). For example, selection for fast, early growth with increased stocking density allows the production of greater numbers of birds in a shorter period of time. Consumers are becoming more and more aware of issues related to welfare and seek validation that meat they consume comes from well-treated animals (Stricklin, 2011).

Much research has been conducted to reduce negative issues related to broiler welfare and to improve their living conditions. In order to improve welfare of broilers, it is important to also look into all aspects of broiler production, beginning with primary breeding companies that are responsible for genetic selection. Duncan (2001) stated that broiler-breeding companies should stop selecting for early fast growth and add value to their strains via other methods. Fast early growth can be connected to metabolic diseases that eventually may lead to mortality by sudden death syndrome or ascites (Bessei, 2006). Many welfare problems could be resolved by altering management factors that promote slower growth rates or by using slow-growing strains in production. However, it is difficult to impose such ideas in the commercial broiler industry where fast growth is directly related to profit the producer will receive as well as production efficiency.

Management practices to which birds are exposed at the farm may affect broiler welfare and the public may criticize these practices. The "Five Freedoms" include a comprehensive set of standards that must be met in order to maximize welfare (FAWC, 2011). Such standards are created to cover all possible aspects of animal production that may compromise the welfare state of animals. The five freedoms are

1) freedom from thirst, hunger and malnutrition,
2) freedom from pain, injury and disease,
3) freedom from discomfort,
4) freedom to express normal behaviour, and
5) freedom from fear and distress.

These freedoms tend to be violated during transportation resulting in welfare issues during transit.

There are multiple management factors that may influence feather wetness. Lighting duration and intensity, stocking density, feed, litter, and ventilation all fall under management factors. Stocking density is an issue that has been brought up many times in the animal-production industry. Both Bessei (2006) and Dawkins et al. (2004) noted the negative effects that can appear with high stocking density. However, Dawkins et al. (2004) states that these negative effects are often dependent on other substantial environmental conditions such as poor air and litter quality, improper temperature, and humidity as well the age of the birds. Improper light duration, intensity, and wavelength can have negative effects on broilers. Lighting is known to influence sight, feather development, and essential biological functions such as body temperature control and digestion (Spearman, 1971; Ohtani and Leeson. 2000; Olanrewaju et al., 2006; Bayram and Ozkan. 2010). Depending on the country, season, flock size, and each producer, recommendations for these management practices may differ slightly (Bessei, 2006). Nevertheless, it is clear that all management practices must be up to standard in order to guarantee high-quality living standards for the birds.

An area of broiler production that is often scrutinized for welfare issues is transportation of live animals (Mitchell and Kettlewell, 1998). According to Duncan (2001), the poorest of broiler welfare conditions are apparent 24 hours prior to slaughter when catching and transportation occur. There is no doubt that birds are exposed to various stressors during transit. Yet, it is inadequate handling of birds and conditions in the vehicle that are identified as the primary components that lead to transportation being a welfare issue (Knowles and Broom, 1990). In most production sites, birds are either caught by hand or by mechanized catchers (Knowles and Broom, 1990; Mench, 2011). By hand, they are caught and carried by legs often in groups. According to Knowles and Broom (1990), manual handling is the most stressful time for broilers and results in more physical damage compared to any other stage in their lives. Regardless of the catching technique, catching of birds subject them to fear and stress due to disruptions in their social and physical environment (Duncan, 2001).

2.2.1 Dead on Arrival (DOA)

On average, 600 million broiler birds are transported to slaughter plants every year in Canada (Agriculture and Agri-food Canada, 2014). Approximately 1.4 percent of these birds are condemned; 0.27 percent being DOA. When taking into account the number of birds transported, 0.27 percent equals 1.64 million birds dead on arrival at the slaughtering plant. Elevated DOA's are partially the result of poor welfare conditions and management practices (Hunter et al., 1999).

In addition to being a welfare concern, high numbers of DOAs are also an economic concern. Gregory and Austin (1992) found that a majority (79%) of DOA birds would have been suitable for human consumption had they arrived alive at the slaughter plant. During winter months of 2013 (November – March), the mean DOA level is higher compared to the rest of the year (0.35% vs. 0.27%, respectively) (Agriculture and Agri-food Canada, 2014). The DOAs during any time of the year can be attributed to many factors, including the stressors the birds are exposed to during transportation.

Among transportation stressors, thermal stress has an important effect on poultry welfare. Thermal environment within a poultry transport vehicle can vary significantly depending on ambient temperatures and vehicle configurations (vents, tarps, etc.) (Burlinguette et al., 2010; Burlinguette et al., 2012; Knezacek et al., 2010). Burlinguette et al. (2012) noted that when the ambient temperatures are below -20°C, temperatures within the vehicle can be between -20.7°C to 21.7°C, where a majority of the birds is exposed to temperatures below 0°C. According to Grandin (1997), thermal stress is the most important cause of DOAs in transit. Wet feathers in combination with various transport conditions may expose the birds to cold stress. Wet feathers, cold exposure temperatures, and improper air circulation increase the risk of hypothermia, which could result in elevated DOAs (Hunter et al., 1999; Knezacek et al., 2010).

Although there is abundant research conducted regarding the welfare of broiler production, there is limited information concerning the effects of wet feathers on broiler welfare and mortality. Hunter et al. (1999) observed a correlation between wet birds prior to transportation and increased DOA rates of poultry. There are recommendations from organizations such as Alberta Farm Animal Care Association (2007), and Canadian Agri-Food Research Council (2003) regarding prevention of transportation of wet birds. Transportation of wet birds continues to occur due to the ambiguity of recommendations and lack of scientific research.

Determining whether a bird is suitable for transportation is typically the truck driver's responsibility. Factors such as the transit duration, weather conditions, stocking density of the truck, and experience of the driver also affect welfare of transported broilers. A combination of wet birds and other factors mentioned above could lead to increased DOAs. It is difficult to classify levels of wetness as being too wet or acceptable and there are no known devices specifically designed to objectively measure levels of feather moisture.

2.3 Feathers

Feathers are key structures that provide insulation and prevention against skin abrasions and infections. In addition, feathers also play a critical role in maintaining carcass quality for broilers (Urdaneta-Rincon and Leeson, 2004). While feathers do have important functions in birds, this part of the bird typically receives very little notice. Feathering could be affected by many factors including but not limited to genetics, gender, nutrition, and environmental conditions. Feather coverage becomes critical especially with market age of birds declining in today's broiler industry (Leeson and Walsh, 2004). Therefore it is important to understand the relationship between these factors and feathers.

2.3.1 Feather Development, Distribution, and Structure

Generally, birds are covered with feathers with the exception of feet, beak, and eyes. Feather density in most species of birds is not consistent for all parts of the body and is segregated into distinct tracts (*pterylae*) (Lucas and Stettenheim, 1972). Structure, distribution, and development are fairly consistent for today's commercial broiler population due to genetic selection.

Feathers are developed in feather follicles with a dermal papilla (Kozak, 2011). These follicles begin growing around day 5 of incubation and by day 6-7 all follicles will be present (Leeson and Walsh, 2004). Keratinization starts around the 13th day of incubation and is completed by day 19 (Leeson and Walsh, 2004). During embryonic development, early feather cover is formed.

Most birds appear to have consistent feather distribution due to varying angles and layering of feathers (Leeson and Walsh, 2004). Approximately 25 percent of the bird is lacking feathers, areas identified as apteria (Leeson and Walsh, 2004), including under the surface of the wings and the central portion of the breast (Lucas and Stettenheim, 1972; Leeson and Walsh, 2004). While the locations of the feather tracts are consistent, plumage (shape, size and appearance of feathers) tends to differ considerably depending on the age, sex, strain, and condition of the bird (Leeson and Walsh, 2004).

Adult bird plumage contains three types of feathers: contour feathers, down feathers and filoplumes (Deschutter and Leeson, 1986). Contour feathers form the outer protective layer. Contour feathers of the wing and tail have traditionally evolved for the purpose of flight, explaining why domestic broilers have less developed contour feathers (Deschutter and Leeson, 1986). Less-developed feathers in broilers can also be likely due to selection for other traits and overlooking flight feathers. Down feathers, prominent in chicks, are also present under contour feathers of adult birds and function as an insulative layer. The development, distribution, and structure of feathers influence the bird's ability to cope with stressors.

2.3.2 Factors affecting feather development

2.3.2.1 Genetics

The rate of feather growth can vary depending on the strain as well in some instances, sex (Gous et al., 1999; Edens et al., 2001). Moreira et al. (2006) compared six broiler strains (Ross 308, Cobb 500, Hybro PG, Hubbard, MPK, and Isa Vedette) based on their feather growth and found that strains do in fact differ in rate of feathering (Cobb 500 and MPK > Hubbard). Fisher et al. (1981) related the consistent greater feather loss observed in females to sex linked differential in rate of feathering. Located on the Z sex chromosome, the feathering gene regulates feather growth (Swaggerty et al., 2006). A recessive *k* allele is responsible for rapid feather growth while a dominant *K* allele is responsible for slower feather growth (Edens et al., 2001; Moreira et al., 2006). *K* and *k* genes were introduced as means of enabling sex determination in one-day old chicks. Fast-feathering one-day-old female chicks can be distinguished from slow-feathering male chicks by observing longer primary wing feathers compared to coverts (females) (Moreira et al., 2006). Wherein, primary wing feathers are the same length as coverts in day-old male chicks. Edens et al., (2001) stated that slow feathering does not affect performance if the birds are being maintained properly, however, better feather development can lead to less downgraded birds due to bruising.

Wing and back feather growth over time has been compared by McDougald and Keshavarz (1984) and they have shown that the length of feathers were greater in females compared to males at 10 days of age. At day 31, males had longer feathers than females but by day 52, there was no significant difference to be observed in feather coverage between males and females (McDougald and Keshavarz, 1984). In addition to having quantitative differences between males and females, there are appearance differences as well. For example, neck feathers (hackles) of males are long and pointed and reach down to wings while hackles of females are less distinctive and blend with other body feathers (Leeson and Walsh, 2004). Similar to hackles, males have longer and pointed tail coverts in the pelvic region (Leeson and Walsh, 2004). Most feather differences between males and females are not present until they are approaching sexually maturity thus they will not be very apparent in broilers during their production cycle.

2.3.2.2 Environmental conditions

Rearing temperature and the type of housing can influence feather development. Although there are no definitive reasons to explain why this occurs, birds reared in summer (27°C) have more feathers than those reared in winter (20°C) (Yalcin et al., 1997). Saleh et al. (2003) claimed that broiler brooding under high temperatures (34°C) did not differ from normal temperature (32°C) brooding in regards to feathering.

According to Edens et al. (2001), the development of feather cover is faster in conventional litter-floor broiler houses compared to caged broiler houses. However, in both types of housing systems studied by Edens et al. (2001), slower growth of breast feathers was observed in comparison to back-feather growth. Edens et al. suggested that this is likely a result of frequent resting on their sternal feathers and experiencing feather loss because of consistent contact with a litter floor or metal bars on caged floors.

Another aspect of housing that has the potential to influence feather development is bird stocking density. Increased housing density often alters the litter and environmental conditions unfavorably. Space, litter quality, and environmental conditions all can affect the quality and quantity of feathers. Coello (2003) stated that competition as a result of high population density has a negative effect on feather structure and arrangement, especially in terms of reduced breast feather development.

2.3.2.3 Nutrition

A number of researchers have observed the relationship between various nutrients and feathering. Nutritional requirements of animals vary depending on their genetics, age, and sex. For example, certain amino acid (example: Cysteine) requirement for slow-feathering males is lower than fast-growing males during the first few weeks when broilers use a significant portion (~10%) of their protein for feather development (Kalinowski et al., 2003). This requirement could be increased if feather development was accelerated by use of some other nutrient source such as organic selenium yeast. A study conducted by Edens et al. (2001) indicated that addition of organic selenium yeast could induce feather development in both slow-feathering males and rapid-feathering females. While Edens et al. noted improvement of feather development with organic selenium supplementation; the mechanism via which it improves has not been further investigated.

In addition to genetics playing a specific role in controlling nutrient requirements for feather growth, general nutrient profile of diet, feed intake, anti-nutrient factors and feed additives also influence feather development (Leeson and Walsh, 2004). Amino acid concentrations in broiler feeds vary significantly between broiler producers (Taschetto et al., 2012). Amino acid balance in the diet is especially important in regards to feather keratin synthesis. High proportion (~85%) of feather protein is represented by keratin, which is characterized by high sulfur content (Leeson and Walsh, 2004). Therefore sulfur-containing amino acids (methionine and cysteine) are most essential for feather growth, texture, and distribution (Leeson and Walsh, 2004). According to Leeson and Walsh, amino acid deficiencies often result in curling of feathers, lack of smooth appearance and abnormal pigmentation. The authors associated these characteristics to not only the deficiency of methionine and cysteine in the diet, but also as a result of diets deficient in other amino acids such as arginine, valine, leucine, isoleucine, tryptophan, and tyrosine.

2.4 Thermoregulation of birds

Similar to mammals, birds are able to maintain their internal body temperature within narrow boundaries over a wide range of ambient temperatures (Whittow, 2000). Peripheral and central nervous thermoregulatory processes begin to develop during the prenatal period and mature during postnatal development (Tzschentke, 2007). From the time when they are hatched, broilers are able to respond to hot and cold conditions successfully, to a certain degree (Whittow, 2000).

Typically, warm-blooded animals adjust to changing ambient temperatures by regulating the level of heat conservation and production to maintain regular core body temperatures (Richards, 1971). In birds, heat loss is managed by respiratory evaporative mechanisms, evaporative cutaneous mechanisms, and sensible heat loss (radiation, convection, and conduction) (Richards, 1971; Cangar et al., 2008; Yahav, 2009). Sensible heat dissipation is driven mainly by the temperature gradient between the bird and its environment, while evaporative heat loss is controlled by the vapor pressure gradient (Liang et al., 2012). Altering the flow of blood to the body surface during cold temperatures or through evaporation of water off the respiratory tract or skin during warm temperatures can alter heat loss from the bird (Richards, 1971; Cangar et al., 2008). Under extreme high temperature conditions, cardiovascular systems will alter the blood flow to areas that are essential for heat loss (Yahav, 2009).

While there has been some speculation as to the thermal neutral zone for broilers (Meltzer, 1983; Pereira and Nääs, 2008), Lin et al. (2006) has identified 18 – 20°C to be the range for optimum temperature for broilers in terms of performance. The difference between core temperature and feathered skin temperature does not vary significantly

(<5°C) when exposed to a range of ambient temperatures. However, the temperature difference between the core and non-feathered areas such as comb, shank and toe varied up to 20°C (Cangar et al., 2008).

2.4.1 Thermoregulatory functions of feathers

Thermoregulatory mechanisms are affected by the nature of bird feathering. Therefore, optimal ambient temperature for a bird can be influenced by the feather coverage as well. It has been found that well feathered birds become more heat stressed during summer months when the ambient temperature is typically high (Richards et al., 2012). Likewise it can be hypothesized that poorly feathered birds struggle more with cold temperatures in winter months. One of the main functions of plumage is providing insulation during cold conditions by trapping warm air between the skin surface and feathers. Skin covered by feathers tends to be thinner compared to exposed areas of skin such as legs and feet, because feathers provide protection from adverse environmental conditions and physical damage (Spearman, 1971).

Birds alter their behaviour and use their feather cover to adapt to changing ambient environments. During cold climates, birds tend to tuck their head under scapular feathers on the back. In order to reduce heat loss from featherless areas, birds will often squat and cover these areas with ventral contour feathers (Whittow, 2000).

2.4.2 Thermoregulation during high temperatures

Broiler performance during high temperatures has been researched extensively (Yalcin et al., 1997). Although birds are able to maintain near-constant body temperatures when the ambient temperatures are extremely high, there is an increase in body temperature due to inadequate physiological and behavioural responses (Deeb and

Chaner, 1999). In addition, the selection for fast growth in commercial broilers has led to the production of more heat and heat stress may become more pronounced (Lin et al., 2006). The average body temperature of adult domestic fowl falls in the range of 41°C to 42°C (Donkoh, 1989). Maintaining broilers at a temperature above the recommended level affects their performance negatively.

Genetic selection for rapid growth and feed efficiency of broilers has allowed the producers to produce heavier birds in a shorter time period for less cost. Although such rapid development should be accompanied by increased size of cardiovascular and respiratory systems as well as their functional competence, it does not (Yahav, 2009). As a result of under development of these systems, there is difficulty maintaining body temperature under high ambient temperature conditions, which in turn causes pronounced effects of thermal stress (Lin et al., 2006; Yahav, 2009).

With high ambient temperatures, food intake is decreased along with food conversion ratio, resulting in decreased body weight (BW) at market time (Donkoh, 1989). Typically, birds reduce feed intake to decrease heat stress in order to maintain homeothermy and avoid hyperthermia (Donkoh, 1989). The end result of depressed food intake is nutrient deficiency causing a poor growth rate. It has been pointed out by Daghir (2009) that the optimum temperature range for growth is not ideal for feed efficiency and therefore temperature is often determined by the market value of the product relative to feed cost. Kampen (1984) found that the highest growth rate of broilers occurs in the range 10-22°C while maximum feed efficiency is at about 27°C. It was later noted by Charles (2002) in a literature review that the optimal temperature for performance of growing broilers is between 18-22°C.

Implementation of proper nutritional, feeding, and environmental strategies can reduce heat stress. Supplementation of nutrients such as vitamins A, E, and C that are critical for broiler performance and immune function benefit birds by maintaining regular functions (Lin et al., 2006). Reducing dietary protein levels during hot temperatures may lower heat production, however, provision of inadequate levels of protein reduce bird performance (Lin et al., 2006). Lin et al. (2006) suggested that if protein content of the diet is to be reduced, it is important to assure that broilers are getting a well-balanced feed ration that will provide all nutrient requirements.

Feed restriction prior to heat exposure can help the bird adjust to thermal challenges. Although reduced feed intake will result in decreased heat production, it also may lead to a reduced growth rate (Lin et al., 2006) requiring an extended growth period. However, in most instances, the market date is preset and the producer must ship the birds as they are, lower BW or otherwise. A producer may also implement a dual feeding program where a high-protein diet is fed during cooler months, and a high-energy diet is fed during warmer months to more easily manage heat production (Lin et al., 2006). When using such a program, it is important to ensure that all essential nutrient requirements are met for broiler growth and performance.

If hyperventilation occurs during heat stress, the blood acid/base balance is disrupted, possibly leading to respiratory alkalosis (Lin et al., 2006). Suppression of growth, resulting from respiratory alkalosis, can partly be corrected through supplementing ammonium chloride (NH_4Cl) or sodium bicarbonate ($NaHCO_3$) and potassium (K) in the diet (Lin et al., 2006). The addition of these electrolytes into drinking water can also stimulate water intake, which in turn can increase heat tolerance (Lin et al., 2006).

Lighting, humidity and heating conditions of the barn can be altered to account for and reduce heat stress during warmer periods. Intermittent lighting, known to improve feed efficiency, has the potential to assist broilers in producing less heat (Lin et al., 2006). Humidity is important when considered with high temperatures and when broilers are attempting to increase heat loss through evaporative cooling. In order for heat loss through evaporation to be successful, surrounding air must be relatively free of water. According to Lin et al. (2006), depending on the age and surrounding temperatures, high humidity (>60%) could have detrimental effects on broiler performance and growth. Although it may be difficult to manage humidity levels in a barn with inconsistent temperatures, special attention must be given to the humidity requirements of broilers.

One of the more common and promising methods to deal with issues related to heat stress is early heat conditioning (EHC) (Lin et al., 2006). When broilers are exposed to high temperatures (~36°C) as chicks, they are more likely to tolerate higher temperatures as adults. Similarly, early feed restriction (EFR) could also benefit broilers in reducing heat stress (Lin et al., 2006). Growth reduction experienced by broilers at the beginning of both EFR and EHC is followed by compensatory growth and typically result in normal or above normal BW at market age (Lin et al., 2006). In addition to the above-mentioned strategies, there is plenty of additional information available in the literature concerning heat stress in broilers that can help the industry manage hot birds (Teeter and Belay, 1996; Tao and Xin, 2003; Renaudeau et al., 2012).

2.4.3 Thermoregulation during low temperatures

Exposure to diverse ambient temperatures alters oxygen consumption and heat production to maintain proper thermoregulation (Yahav et al., 1997). Yahav et al. (1997) found that exposure of broilers (Cobb, males, 28d) to cooler temperatures (10 and 15°C) resulted in increased packed cell volume and heat production when compared to birds housed under 'normal' and high temperature (30 and 35°C) conditions.

When birds with wet feathers are exposed to low temperatures it compromises their ability to maintain adequate thermoregulation, resulting in decreased core body temperatures and increasing the risk of developing hypothermia (Hunter et al., 1999). During hypothermia, body temperature is decreased as a result of heat loss exceeding heat production. The initial response to cold temperatures is an attempt to decrease heat loss while increasing heat production. However, when the body is unable to maintain the core temperature, it begins to drop eventually leading to hypothermia. This, combined with compromised thermoregulatory mechanisms, suggests that a bird's ability to increase blood flow to the skin surface is diminished. Good plumage, by providing insulation, can assist the birds in decreasing the risk of acquiring hypothermia.

Critical ambient temperatures depend on the size, feather density, and acclimatization state of the bird (Whittow, 2000). As ambient temperatures approach lower critical body temperatures, heat loss tends to exceed heat production. In order to prevent a low core body temperature, the catabolic rate of the body is increased while attempting to use physical thermoregulatory mechanisms to lower metabolic effort. Feathers become an important asset in this process. Thermal conditions of the bird can be detected by their behaviour. Behaviour can also assist a bird to adjust to varying thermal conditions and allow it to save energy, conserve water and reduce thermal stress (Whittow, 2000). Cold birds will likely huddle together and stay close to a heat source. Birds fluff their feathers to increase insulative ability. When feathers become exposed to excessive amounts of moisture they become difficult to ruffle and their insulative ability is diminished (Nicol and Scott, 1990).

According to Hunter et al. (1999), broilers are able to survive ambient temperatures of -4°C, provided they are kept dry. The authors observed that when broilers are exposed to moisture, even temperatures as high as 8°C could lead to moderate hypothermia. Exposure to moisture, low temperatures, and air movement combined can disturb effective feather insulation. Typical management practices of feed and water withdrawal prior to transportation increase the risk of acute hypothermia as the birds are deprived of readily-available energy for thermogenesis (Hunter et al., 1999).

The absence of thermoregulatory functions does not always denote hypothermia. An absence of thermoregulatory functions typically occurs with a lack of feed and is indicated by temporary cessation of shivering, reduced heat production and decreased body temperature (Whittow, 2000). Given proper feed, birds are able to react to hypothermia resulting from low ambient temperatures with regular thermogenesis (Whittow, 2000). In the case of broilers, where feed and water are removed prior to transportation, there is potential to face hypothermic conditions with an absence of regular thermoregulatory functions.

Sturkie et al. (1967) demonstrated that chickens exposed to cold temperature (0-12°C) conditions have higher resting heart rates compared to those exposed to normal (23-25°C) or high temperatures (24-32°C). It is important to identify and address detrimental effects of thermal stress and find techniques to measure and alleviate this stress inflicted on the broilers. In order to address thermal stress, events leading to such circumstances must be understood first.

2.5 Broiler barn ventilation

Ventilation requirements for broiler barns are different during winter months compared to summer months. When environmental conditions change, the ventilation system employed in a barn may also change. Management practices must be altered accordingly to accommodate needs of the birds while minimizing costs associated with such practices. In addition, different locations in the barn may present varying environmental conditions due to variations in localized heating, cooling and ventilation (Miles et al., 2008). In order to maintain broiler welfare and optimize growth, these practices must be managed carefully.

Requirements of ventilation in livestock barns have always been a concern (Seedorf et al., 1998). Sufficient ventilation is required to keep birds at an optimal temperature to maximize growth production. Due to design, maintenance, and installation shortcomings, ventilation rates may not be in perfect balance with the requirements (Seedorf et al., 1998). Ventilation is known to be one of the major energy inputs in broiler production along with heating (Feddes et al., 1984). During winter, ventilation is important in removing excess moisture and therefore inadequate ventilation can result in moisture accumulation within the barn (Feddes et al., 1984; Esmay and Dixon, 1986). Coella (2003) identified management practices such as inadequate ventilation as a cause of excessive litter moisture accumulation. However, it is common to reduce ventilation and conserve heat during winter months (Hermans et al., 2006).

In order to guarantee adequate ventilation is being provided, the quantity of moisture produced by birds, feed, and drinkers must be taken into account (Feddes et al., 1984). Heat and moisture can enter or leave the barn with a number of other substances. Some examples are feed, equipment, straw, water, and air. In addition, heat from adjacent rooms or halls can enter through the walls. While heat and moisture enter the building they must also exit to maintain proper environmental conditions in the barn. In addition, housing design and weather conditions can also influence the moisture production in the barn. For example, there could be excessive litter moisture from condensation due to daily temperature changes, poor insulation, or limited ventilation available during winter (Coella, 2003). Reduced ventilation means less heat exiting the building. Thus the need for additional heat to be supplied to the barn is lower. This is a recognizable decrease in cost to the producers and occurs more during winter when heating costs are high. However, while less heat is exiting the barn at the same time less moisture is also exiting. A combination of moisture produced within the barn and reduced ventilation may lead to moisture accumulation.

Warmer air has an increased water-holding capacity (Karl and Trenberth, 2003). Vice versa, with decreasing temperatures, the water-holding capacity of air is decreased. Condensation depends on the vapor pressure of water where, with higher pressures, water would condense. Excess moisture may accumulate in the barn and begin to be absorbed by biological materials. Litter, bedding, feed, and feathers may absorb this excess water (Hermans et al., 2006). Such conditions can lead to birds having wet feathers and this may be a risk factor prior to transportation.

2.5.1 Wet litter

Inadequate ventilation systems can be indicated by above-normal moisture levels closer to the sidewalls near the end of the grow-out period (Miles et al., 2008). As most producers decrease the rate of ventilation supplied during winter to cut down on cost related to heating, inadequate ventilation results in poor litter quality (Feddes et al., 1984). Prevalence of wet litter is higher during winter months compared to the rest of the year (Hermans et al., 2006). Wet litter has higher moisture content than what is typically expected. Feed, season, drinker design, temperature, and humidity in the barn are among other risk factors for wet litter (Hermans et al., 2006).

Weaver Jr. (1991) explored the effects of relative humidity (RH) and air movement on litter moisture and ammonia (NH_3) levels. The study indicated that when RH is higher, litter moisture and NH_3 levels increased. In addition, litter caking was evident when RH was high. Although the results gathered from different air circulation speeds were not as dramatic as the results from RH levels, the study suggested that with decreased air circulation, the litter contained greater amounts of moisture.

NH_3 produced from litter affects air quality resulting in poor animal productivity and is a concern to the environments surrounding broiler barns (Miles et al., 2013). NH_3 generation is mainly attributed to litter properties such as temperature, moisture, pH, and N-content (Miles et al., 2013). Reduction in NH_3 levels could be achieved by increasing ventilation (Xin et al., 1996).

High-density areas of the barn such as feeders, waterers, and exhaust fans tend to have litter that is high in moisture and appear cake-like (Miles et al., 2008). An experiment conducted by Miles et al., (2013) showed that the moisture content (MC) levels of rice hull litter near the waterers were significantly higher than those near sidewalls and feeders. Poor litter conditions are often associated with low-quality carcasses and poor welfare conditions. Coella (2003) noted that it is common to observe feather alterations (feather weight, barbules and barbicels not bending, feather strength, feather shafts show gangrenous material in the base) in commercial conditions due to improper environmental conditions (ventilation, management, feed restriction programs, and population density). Coella (2003) identified wet litter as a probable cause of altering (shape altering by means of barb and barbules separation) breast feathers and leaving delicate skin unprotected which will result in downgraded meat. There is evidence suggesting that birds growing in wet-litter conditions tend to increase feed intake (Hocking and Wu, 2013) possibly because of reduced thermal comfort. However, the increase in feed intake in this study was not adequate to recompense for the increased energy requirement for maintaining body temperatures after observing a decrease in temperature (Hocking and Wu, 2013).

Although the animal industry does not have any known methods to measure feather wetness of live birds, there are plenty of other industries that have been testing moisture content of biological materials for quite some time.

2.6 Measuring moisture in other biological materials

2.6.1 Soil

Soil moisture is measured for the purpose of observation and control of agriculture-related practices (Kaatze and Hubner, 2010). One important reason to measure soil moisture is for irrigation, which aims to provide sufficient moisture for plant growth. Lack of moisture monitoring leads to soils that are either over or under-watered

(Luke, 2006). The oldest method of monitoring soil moisture is by feel. This is not a reliable or accurate technique that can be used to indicate how much water is in soil or when the next watering should occur.

There are various other soil-moisture-measuring techniques that are much more reliable and provide accurate data. They use direct, indirect, and remote techniques (Alberta Agriculture and Rural Development [AARD], 2012). Direct measurement extracts water from soil with the use of evaporation, leaching or chemical reaction. Indirect methods measure a property of soil that is affected by moisture. Remote measuring of soil moisture depends on electromagnetic energy emitted or reflected from the soil surface. With remote methods, non-contact measurements and measurements from great distances are possible (AARD, 2012).

Many electronic companies have developed hand-held moisture meters that have been assessed by soil science researchers (Balla et al., 2013; Benor et al., 2013). NASA is developing a much more technologically advanced method for soil moisture measurement of the earth called the Soil Moisture Active Passive (SMAP) mission (Entekhabi et al., 2010). Currently, land surface models (LSMs) and the Global Land Data Assimilation System (GLDAS) are used to detect land moisture throughout the world (Koster et al., 2009).

2.6.2 Building materials

In the building industry, determining moisture content of material used is very important. Knowing the moisture content of wood can help in understanding the time required for drying properly to prevent damage to the wood and to assure high-quality products to the users (Kaatze and Hubner, 2010). There are many moisture-sensing meters developed specifically for the detection of wood moisture such as Aqua-Boy, General MMH800, Extech 257, and Delmhorst RDM-25 (Forsen and Tarvainen, 2000).

Wood-moisture meters available in the market can be separated into two main types; those that sense differences in electrical resistance and capacitance (Forsen and Tarvainen, 2000). Resistance meters measure the electrical resistance of wood where increased moisture content causes reduced electrical resistance. Capacitance meters respond to differences in dielectric constant between a material and water (Forsen and Tarvainen, 2000). With increasing moisture in a material, the dielectric constant slowly increases (Gadani and Vyas, 2008).

Straw bales are being used in UK and some other parts of the world for building construction (Goodhew et al., 2004). Although straw bales can provide good insulation, their organic nature is susceptible to degeneration caused by microbes that thrive in a moist and high-temperature combination (Goodhew et al., 2004). Goodhew et al. regards a resistance based wood-disc moisture sensor to be the most common method for testing moisture content in straw-bale walls. These sensors are inexpensive, easy to use and reasonably accurate.

In addition to wood and straw-bale moisture sensors, there is a variety of sensors available for other building materials. Most moisture meters that measure wood moisture are also equipped to measure moisture levels in other building materials such as concrete and gypsum. Erich and Pel (2011) identified seven ideal requirements that should be met when measuring moisture content. These requirements are very similar to qualities desired by any other industry that is measuring moisture content. The list includes high accuracy, reproducibility, portability, low cost, and non-destructibility (Erich and Pel, 2011).

2.6.3 Grain

In the grain industry, moisture is tightly monitored to ensure grain quality and proper storage conditions. In addition, grain moisture content has an effect on mass of grain and economic profit (Hellevang, 1995). Moisture content plays an important role during pre-harvesting as well as in all stages postharvest (Grolleaud, 2002). Pre-harvest maturity of the grain can be determined through the amount of moisture present. After harvesting, knowing the moisture content of grain aids in deciding methods and durations for drying. Moisture level indicates whether there is a need for treatment prior to processing grain products. Storage conditions of grain are monitored through the moisture content as well. The moisture levels of grains can be determined by a variety of techniques, directly or indirectly. The Canadian Grain Commission (2012) provides guidelines for proper measurement using selected devices.

Most producers use their personal experience in the field to estimate moisture content of grain. Whether this is by touch, sight or smell, these estimates are simply subjective, not objective measurements. Moisture can directly be measured using a gravimetric technique where the difference in mass between a wet and dry sample is equal to the moisture loss. Indirect measurement of grain moisture levels depends on electrical characteristics of grains. The grain industry has numerous simple hand-held devices for portable testing as well as complex devices for large storage centers.

2.6.4 Cotton

The moisture level of cotton at the time of harvest determines the processing conditions and quality of cotton. Various companies including Delmhorst, Panomex, and Aqua-Boy have cotton moisture sensors available commercially. Some of the common approaches for measuring cotton moisture are thermal drying, spectroscopy, change in electrical or dielectrical properties and compression (Gordon et al., 2010). For measuring moisture in lint cotton, an oven-drying technique is used in most standard testing methods (Montalvo and Von Hoven, 2008). Similar to other industries, loss of weight is taken as the amount of water removed and later this is expressed as a percentage of moist or dry material.

If the moisture level in cotton is too high, the quality is considered to decrease. Some warehouses in United States have started to test the moisture content of arriving cotton-bales and adjust prices if it is above 7.5% (Byler et al., 2009). Similar to other industries that need to test moisture levels, the cotton industry also has more than a few specifically designed moisture meters. Byler et al. (2009) tested and compared seven moisture meters for their accuracy, precision, range, price, and ease of use. Their findings concluded that although these meters can be used to provide a general indicator of cotton bale moisture, depending on the location these bales originated, meters produced different results. Byler et al. advised that these cotton moisture meters should not be used for important tasks such as pricing.

2.6.5 Dielectric properties and infrared techniques

Measurement of dielectric properties in porous material allows for estimation of moisture content. Dielectric properties affect the ease with which electromagnetic fields can be created within the material (Nelson, 2008). By this, it is possible to use the single physical property, permittivity, over a range of scales and make an estimation of moisture content (Robinson et al., 2003). With today's advanced technology, there is a variety of moisture-sensing devices that use dielectric properties to estimate moisture present in a material. The success of using dielectric properties relies on many factors including accuracy and consistency of the devices being used. It is important that sensing devices are able to detect the permittivity of the selected material with consistency, precision, and accuracy. Because most of these devices produce a value of moisture content, it is equally important to ensure that the conversion pathway from permittivity to moisture content is correct (Robinson et al., 2003). Techniques using dielectric properties and other electromagnetic field interaction with water are being practiced widely by many industries (Kaatze and Hubner, 2010). Such practices are known to be continuous, fast, and stable. In addition they can be non-contact, non-invasive and measure moisture in real time (Kaatze and Hubner, 2010).

Infrared sensor techniques used to monitor surface temperatures can also be applied to measuring moisture content in theory. An infrared beam directed onto the material measures the material's temperature or moisture content based on the ratio of absorbed and reflected wavelengths. Kett's near infrared moisture meter and GreCon's moisture analyzer IR 5000 are two devices that use infrared technology to measure moisture. They are utilized in detecting moisture in a number of materials including food, chemicals, plastics, paper, textiles, and wood. This is one of the only techniques that is truly noncontact and it detects electromagnetic reflectance at specific wavelengths. Infrared sensors can be affected by the material's particle size, shape, density, and colour.

2.6.6 Disadvantages of moisture meters

Use of gravimetric techniques to determine moisture content of a certain material is reliable and typically provides accurate results if proper guidelines are being followed. Challenges with such techniques arise when moisture content is needed immediately. This is where moisture meters, especially hand-held devices, become practical and necessary.

As it has been previously discussed in this paper, there are multiple moisture meters available to the consumer today. With one moisture meter company claiming to be better than another, it is difficult to choose a meter without doing extensive research. In order to compete, moisture-meter developers rarely share the procedure used to acquire the reading in their meters. For most buyers, the physics behind these meters are simply a foreign language.

Not all moisture meters are alike. Depending on the material density, ambient temperature, air humidity, and the quality of the material being tested, they will interact and produce a value accordingly. The relationship between dielectric constant and moisture within the material being tested varies depending on the material being tested. Most of the moisture meters are developed and calibrated to measure moisture levels within one type of material. When a moisture meter is using a calibration equation designed for a specific material, accuracy will likely suffer if it is used to sense the moisture level within a different material.

When selecting a moisture meter, it is critical to select one that is suitable for the type of material being tested. Erich and Pel (2011) list ideal requirements for moisture testing that can be applied for any moisture meter. For ease of use, a hand held and portable meter that is able to produce a fast response is preferred. Moisture meters should be sensitive to changes in moisture content of a material but should not be over-sensitive where they are reacting to changes in environmental conditions. Precision plays an important role in moisture meters along with accuracy. It is critical that a meter is able to produce accurate values that are repeatable. These are some of the desirable qualities of moisture meters. Depending on the material being tested, a moisture meter may require other more specific qualities.

Transportation of wet birds is a significant welfare issue, especially in winter months. Although there are recommendations regarding this matter, there are no firm guidelines to indicate the level wetness that is detrimental for the bird to travel. Unlike other biological industries, there are no known devices that are able to measure moisture levels in feathers of live birds. If a moisture-measuring technique or device can be identified for the use of feather wetness it is possible to prevent wet birds from being transported. By minimizing the number of wet birds that are loaded on to the transportation truck, bird welfare and overall profit to the industry can be improved.

2.7 Objectives

The primary objective of this research, as a whole, was to determine the capability of various commercially available moisture-sensing devices to measure feather wetness. The performance of selected devices was evaluated under both laboratory and field conditions.

2.8 Hypothesis

Commercially available moisture-sensing devices are capable of measuring and indicating feather wetness.

Preface to Chapter 3.0: Evaluation of commercially available devices to indicate the level of feather wetness in laboratory settings.

The primary objective of this work was to evaluate commercially available moisture-sensing devices and an infrared camera in their ability to measure feather wetness. This experiment was conducted in a laboratory setting utilizing artificial feather beds created using broiler back feathers. This chapter will evaluate five commercially available moisture-sensing devices, an infrared (IR) camera, and moisture-sensitive paper on their ability to measure feather moisture. The final goal from this research is to identify several devices that show promise to be tested under field conditions, which is then discussed in the next chapter.

3.0 EVALUATION OF COMMERCIALLY AVAILABLE DEVICES TO INDICATE THE LEVEL OF FEATHER WETNESS IN LABORATORY SETTINGS.

3.1 Abstract

Five commercially available moisture-sensing devices (Construction 1, Construction 2, Construction 3, Hay sensor, and Leaf sensor), an infrared (IR) camera, and moisture sensitive paper were examined to evaluate their ability to detect and measure moisture in feathers. The devices, with the exception of the Leaf sensor, produced moisture percentage readings when in contact with the material being tested. The Leaf sensor provided a dielectric constant value that changed depending on the moisture content of the material. The theory that the insulative characteristics of the material will change, depending on the moisture present in a material was the primary reason for using the IR camera in this experiment. Moisture-sensitive paper, depending on the amount of moisture it comes in contact with, alters its colour. Twelve artificial feather beds were created using broiler back feathers and plastic grids. They were created at four different densities to account for varying feather density in birds present in commercial conditions. For each density, seven treatment levels of moisture were applied. Each treatment was repeated 10 times. True moisture content of the feathers was determined using a simple gravimetric technique. The devices, the IR camera, and the moisture-sensitive paper were evaluated using accuracy, consistency, and sensitivity by comparing adjusted-R^2, standard error, and regression slope values, respectively. In order to mimic commercial conditions where separating birds based on feather density is difficult, feather density was not factored into the main analysis. There was a significant linear relationship

($P \leq 0.05$) between the true moisture content and the device readings, IR camera temperatures, and moisture levels predicted by the moisture-sensitive paper. Construction 1, 2, and 3 proved to be capable of providing the most sensitive readings whereas construction 1, Hay sensor, and Leaf sensor produced the highest adjusted-R^2 values (variability explained by the model). Construction 1 and Hay sensor had the smallest standard error values demonstrating the ability to produce consistent readings. Results show that it is possible to measure feather moisture with commercially available moisture-sensing devices. Based on these results, Construction 1 and Hay sensor were selected for further testing using live birds in commercial conditions.

3.2 Introduction

Transportation of broilers is a regular and a necessary step in broiler production. All broilers are subjected to transportation at least once during their lifetime (Mitchell and Kettlewell, 2009). Duration of transportation can vary from a few minutes to hours. Mortality in transit is a major welfare concern to the poultry industry. High mortality during transit can indicate poor welfare conditions and result in decreased profit. Mortality in transit can result from on-farm conditions, loading damage or pre-slaughter transportation (Bayliss and Hinton, 1990; Nijdam et al., 2004; Vecerek et al., 2006). There is substantial interest in improving poultry welfare during transport and reducing the number of birds arriving dead (DOAs) at the processing plant (Thomson et al., 2011). Although there has been research conducted to improve transportation conditions, there has been little effort invested to detect at-risk birds for mortality at the farm (Thomson et al., 2011).

Throughout the process of transportation, there are typically two types of losses that can occur, live weight shrink and DOAs. During the western Canadian winter months, transportation conditions are such that the birds tend to become either too hot and develop hyperthermia or cold and wet resulting in hypothermia (Knezacek et al., 2010). These conditions are harmful to their welfare and eventually lead to increased occurrences of meat quality defects, shrinkage and DOAs (Watts et al., 2011).

Wet birds prior to transportation have been known to correlate with higher DOA rates of poultry (Hunter et al. 1999). Wet birds are especially apparent during the winter months, when the barn ventilation may be reduced to decrease the cost of production (heating) (Hall and Menges, 2012). Reduced ventilation results in moisture accumulation within litter, feed, as well as bird feathers (Hermans et al., 2006). In addition to DOAs being a welfare concern, these also result in a financial loss to the broiler industry.

Similar to the previous few years, DOAs were the second leading cause for condemnation of broilers in 2013, following sub-cutaneous conditions (Agriculture and Agri-food Canada, 2014). In total, 1.4 percent of birds were condemned after arrival at the slaughter plant with 0.27 percent being DOA. While these values may appear to be small, when taking into consideration that over 600 million broilers were transported, the end results were 1.64 million birds condemned as a result of DOA. A study conducted by Gregory and Austin (1992) showed that 79 percent of DOA birds would have been suitable for human consumption had they survived the transportation process.

Transportation often subjects broilers to various stressful conditions, such as feed and water withdrawal, motion, social disruption, noise, and environmental changes (Nicol and Scott, 1990). According to the Canadian Recommended Codes of Practice, transportation of at-risk birds should be avoided (Canadian Agri-food research Council [CARC], 2003). Birds at risk include those that are visibly sick, injured, disabled or wet. Even with general recommendations from organizations such as Alberta Farm Animal Care Association (2007), CARC, and European Food Safety Authority Panel on Animal Health and Welfare (2011) regarding the state of broilers prior to transportation, wet birds continue to be transported. Determining whether a bird is suitable for transportation is typically the truck driver's responsibility. Lack of scientific information, ambiguity of recommendations, and unavailability of a method to quantify a bird's wetness leads to wet birds being transported and increased mortality along the way.

While there are no known devices currently available to quantify feather wetness of live birds, there are a number of industries that have been measuring moisture content for decades. The conventional method of determining moisture content via a gravimetric technique is not practical for current research purposes. It would be ideal to find a hand-held device that would detect or measure the level of moisture immediately upon contact without destroying the sample (feathers of the bird).

Knowing the moisture content of soil is extremely important for many reasons especially with the increasing population of the world where the demand for fresh water is high (Huisman et al., 2003). The field of soil science has come a long way since the method of monitoring soil moisture by its feel. Currently there are numerous direct, indirect and remote techniques that can measure soil moisture and provide reliable and accurate data. Direct methods are often invasive where the water is extracted from soil using evaporation, leaching or chemical reaction. Indirect methods use properties of soil that are affected by moisture. Remote measuring of soil moisture, relatively new to the field, depends on electromagnetic energy emitted or reflected from the surface of soil.

Measurements of forage and grain moisture are crucial when making decisions regarding harvesting and storage. In addition, quality, quantity and economic profit all depend on the moisture content of the grain (Hellevang, 1995). The Canadian Grain Commission (2012) has listed multiple techniques to properly measure grain moisture content. Most farmers tend to use their personal experience in the field to estimate moisture content. Similar to measuring soil moisture, grain moisture can also be measured directly and indirectly. For various types of grain present in the market today, there are specific moisture sensing devices that will provide reliable information to the farmer.

Level of moisture in cotton has been used to determine the quality as well as the price. Gordon et al. (2010) lists thermal drying, spectroscopy, electrical, or dielectric properties and compression as most common approaches to measure moisture content of cotton. There are not as many well-known portable moisture-sensing devices for the cotton industry. However, there are studies examining cotton moisture meters and their effectiveness as its importance is being recognized (Byler et al., 2009). In the near future, one can expect to see more moisture meters specific to cotton to be developed and available commercially.

There are multiple companies that are constantly marketing a number of moisture meters that claim to measure moisture level of building material better than their competitors. In order to guarantee good quality and durable products to the customer, measuring moisture content of the building material is critical (Kaatze and Hubner, 2010). Depending on the type of material being used there are specific moisture meters available. Most of these moisture-sensing devices are non-invasive to ensure that the material is not destroyed in the process of measuring moisture.

Whereas, there are numerous moisture-measuring devices available, techniques used to acquire moisture content from a specific material in each device is known only to a few. Moisture measurement methods can be both direct and indirect. This includes infrared drying, distillation, electric conductivity, capacitance, microwave, infrared reflection/absorption, thermal conductivity, and neutron radiation (Wernecke and

Wernecke, 2014). Additionally, there are multiple other techniques that exist due to physical and chemical inconsistencies of water and the sampled material.

Although there have not been any new discoveries related to moisture measuring techniques in the last few years, there has been great advancement in improving existing techniques and extension of the range of application significantly (Wernecke and Wernecke, 2014). The new generation of moisture-sensing devices can be characterized by high precision and accuracy, compact design, low electrical power consumption, and the implementation of microprocessors for advanced controlling and analysis (Wernecke and Wernecke, 2014).

A common indirect technique used in measuring moisture is the measurement of dielectric properties (electrical and magnetic energy). A material is classified as dielectric if it has the ability to store energy when an external electromagnetic field is applied. These materials have a set of unique electrical characteristics that are dependent on their dielectric properties. Variations in moisture levels are detected when an electric potential is applied through the electrodes of a sensor and monitoring the changes in electrical characteristics of a material.

Most commercially available moisture sensors use capacitance, conductance, resistance or the change in dielectric constant in ways to monitor moisture. Capacitance is the ability of a body to store an electrical charge. The ease with which an electrical current passes is electrical conductance. The inverse quantity is electrical resistance, opposition to the passage of an electrical current. Change in dielectric constant can be defined as the ease with which magnetic field can be created. Soltani and Alimardani (2011) concluded that by monitoring the change in dielectric constant of seeds and grain, moisture content could be predicted reliably. Most of the devices used in this experiment mainly employ conductivity as the technique to predict moisture.

An image acquired by thermal imaging will display the surface temperatures. Thermal imaging involves the detection of infrared radiation (heat) emitted from an object. Any object that has a temperature above absolute zero (-273.15°C or 0°K) will emit infrared radiation (McCafferty, 2013). Thermal imaging for the purpose of monitoring body temperatures of birds has been used for a few decades. Thermal imaging has limitations when the birds are in a large open area and it becomes difficult to control the source of radiation. Radiation emitted from the surrounding area can produce inaccurate results. The lens used in the camera has a great effect in the spatial resolution and can be used to manage such situations (McCafferty, 2013). It may also be possible to perform a calibration if the surface temperatures of surrounding objects are known. With various lenses and settings available, infrared cameras are designed to be suitable for field conditions with various temperatures and humidity levels (McCafferty, 2013). It is assumed that as the amount of moisture in feathers increase, their insulative ability decreases and heat escapes from the inside of the body to the surface of the feathers. Because thermal imaging is associated with detection of infrared radiation (heat) emitted from an object, in theory it may be possible to detect the temperature of the feathers and develop a relationship between temperature and moisture (McCafferty, 2013).

Moisture-sensitive paper is used for a variety of everyday situations including, water leak detection in roofs, between walls, and inside car doors. In the case of agricultural usage, it can be helpful in checking spray distribution, droplet density from aerial and ground spray applications and for droplet sizing. Moisture-sensitive paper is able to provide information (subjective) regarding overdosing or under dosing in these situations.

The objective of this experiment was to evaluate commercially available moisture-sensing devices and techniques in terms of their ability to monitor feather wetness in a laboratory setting and select devices to be tested within a commercial environment.

3.3 Experimental Design

The majority of the testing occurred in a temporary green house (2.1m X 1.9m X 1.9m) (Homtronix, model JS-GH02E-2) in the College of Engineering at the University of Saskatchewan. The green house was used as a means to control environmental conditions. Inside the green house, a small tent (0.75m X 0.60m X 0.60m) was set up where actual testing of the devices was conducted.

3.3.1 Conditioning feather swatches

Artificial feather beds were created using back feathers (5-8cm) collected from market age broilers and sewn to a plastic grid (15cm x 15cm) (Figure 3.1). Feathers were thoroughly washed and dried several times prior to swatch attachment. In order to account for different feather densities present in a typical broiler flock, feather swatches contained different amounts of feathers (Table 3.1). Twelve swatches were created in total (n=12), three for each of the feather densities.

Table 3.1 Number of feathers attached to each swatch based on density

Feather Density	Spacing Between Feathers		Feathers per Row	Number of Rows	Total Feathers
	Rows	**Columns**			
100%	2	2	20	18	360
65%	3	2	19/20*	12	234
45%	3	3	13/14*	12	162
25%	4	4	10	9	90

*The number of feathers in row alternated.

Swatches were conditioned with varying levels of moisture by spraying distilled water specific to swatches and moisture levels over the swatch and leaving them in a sealed plastic bag for approximately 15-16 hours (Table 3.2). Different moisture levels in Table 3.2 were used to account for potential levels of moisture birds might encounter within barns. The amount of moisture applied to each swatch was based on the dry weight of the feathers. Following table 3.2, moisture required for a specific level was measured into a small spray bottle. The bottle was held approximately 15 cm away from the swatch when spraying. Supplementary testing was conducted with 0.25 and 0.75 moisture treatment levels after an assessment of initial data to account for all possible moisture conditions that are present in actual field conditions.

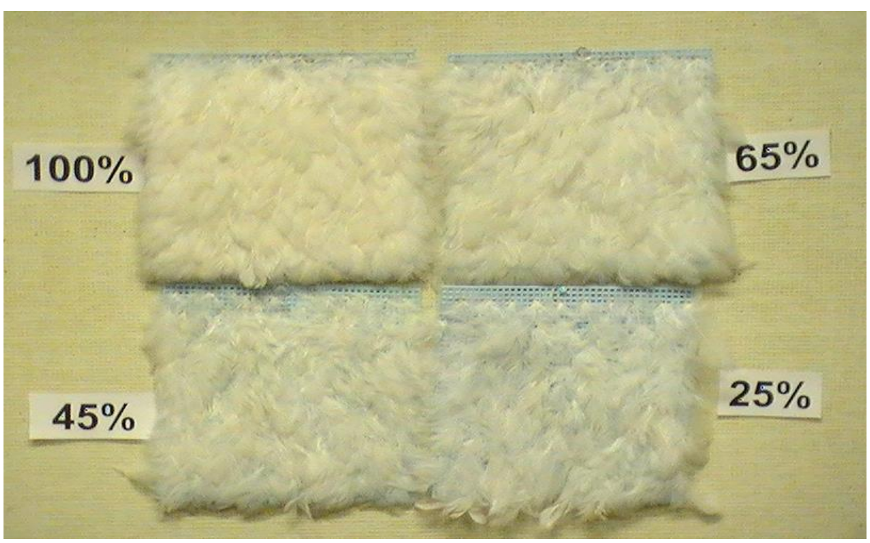


Figure 3.1 Feather swatches at different densities

Table 3.2 Feather Coverage and the amount of distilled water related to seven moisture levels applied to each of the swatches for all the moisture application treatments

Swatch	Weight of feathers* (g)	Feather density treatment (%)	Weight of distilled water applied for each treatment level (g or ml of water)						
			0	*0.25*	*0.5*	*0.75*	*1.0*	*1.5*	*2.0*
1	5.9	100	0	1.5	2.9	4.4	5.9	8.8	11.7
2	6.1	100	0	1.5	3.0	4.6	6.1	9.1	12.2
3	3.5	65	0	0.9	1.7	2.6	3.5	5.2	6.9
4	4.2	65	0	1.0	2.1	3.1	4.2	6.2	8.3
5	2.7	45	0	0.7	1.4	2.0	2.7	4.1	5.4
6	2.4	45	0	0.6	1.2	1.8	2.4	3.6	4.8
7	1.6	25	0	0.4	0.8	1.2	1.6	2.4	3.2
8	1.6	25	0	0.4	0.8	1.2	1.6	2.3	3.1
9	3.7	65	0	0.9	1.8	2.7	3.7	5.5	7.3
10	6.5	100	0	1.6	3.2	4.9	6.5	9.7	13.0
11	3.0	45	0	0.8	1.5	2.3	3.0	4.6	6.1
12	1.7	25	0	0.4	0.9	1.3	1.7	2.6	3.5

* Does not include the plastic grid weight

3.3.2 Data Collection

For the purpose of this experiment, six devices and one type of moisture-sensitive paper were used on the feather swatches (Figures 3.2-3.8).

The Decagon Leaf Wetness sensor (Leaf sensor) is a leaf-shaped sensor used primarily to detect water and ice-formation (Figure 3.2). The non-hygroscopic coating on the sensor reduces the likelihood of producing false wetness readings. The sensor requires a data logger in order to collect the data. The moisture is detected using the change in dielectric constant that is associated with varying moisture levels. With increasing moisture in a material, the change in dielectric constant also increases.

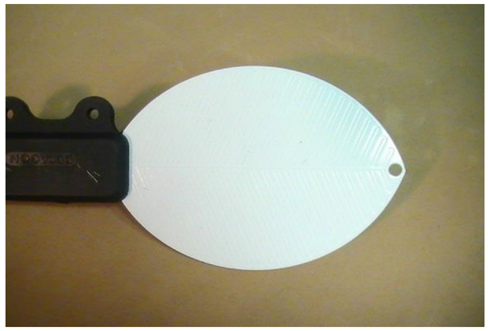


Figure 3.2 The Sensor pad of the Decagon Leaf Wetness sensor (Dimensions: 11.2 cm x 5.8 cm x 0.75cm)

The Delmhorst FX-2000 Hay moisture meter (Hay sensor) (Delmhorst Instrument Co., 510INS-0009, Towaco, NJ**)** was created for convenient on-the-go moisture monitoring during the baling process (Figure 3.3). During normal operation, the sensor pad is installed inside the bale chamber of a baler and uses changes in electrical conductivity to sense moisture levels in the hay. For this experiment, a 1986 Bale sensor electrode (white pad) was attached and used to measure feather wetness.

Figure 3.3 Delmhorst FX-2000 Hay moisture meter. The sensors are located on the white pad.

The General MMH800 sensor (Construction 1) (General Tools & Instruments, New York City, NY) is designed for measurement of wood and building material moisture (Figure 3.4). Two separate settings are possible for wood and building materials. The device consists of two pin sensors on top (a) and a pad sensor at the back (b) for non-destructive readings. For this experiment, the wood setting and the pad sensor were used. This device monitors the change in electrical conductivity to produce a moisture percentage.

Figure 3.4 The general MMH800 sensor. Pin sensors are located at the top (a) and a pad sensor is located at the back (b) of the device.

The Extech MO257 (Construction 2) (Extech Instruments Corporation, Nashua, NH) measures the moisture levels within wood and other building materials, using a single setting (Figure 3.5). The ball located at the top of the device functions as the measurement sensor. With the ball sensor and high frequency sensing technology, it is capable of obtaining non-invasive measurements. By monitoring the electrical capacitance in a material, this device produces a moisture percentage reading.

Figure 3.5 The Exetch MO257 moisture sensor with the ball shaped sensor at the top of the device

The Extech MO265 (Construction 3) (Extech Instruments Corporation, Nashua, NH) is capable of measuring moisture in wood and other building materials including particleboards, carpeting, sheet rock, and ceiling/bathroom tiles (Figure 3.6). Similar to the General MMH800, this device also consists of pin sensors at the top and a pad sensor in the back. Similar to Extech MO257, change in electrical capacitance of a material is used to monitor the quantity of moisture present in the material, which is then outputted as a percentage reading.

Figure 3.6 The Extech MO265 sensor. Pin sensors are located at the top (a) and a pad sensors is located at the back of the device (b)

The Infrared camera (Therma CAM^{TM} SC660, FLIR systems Inc., Burlington ON) used in this experiment (Figure 3.7) was capable of supplying infrared images of superior quality and accurate temperature measurements. IR image pixel density was 640 x 280 pixels. The IR camera is capable of detecting temperatures in the range of -40°C to +1500°C with +/- 1°C accuracy.

Figure 3.7 FLIR systems ThermaCam S60

(Image from http://news.thomasnet.com/fullstory/infrared-camera-includes-firewire-digital-output-17793)

Cobalt chloride moisture-detection paper from Indigo Instruments changes colour from blue to varying shades of red when it is exposed to moisture. Water sensitive paper from TeeJet Technologies (Spraying Systems Co., Wheaton, Il) is specially coated and is often used for evaluation of spray distribution, swath widths, droplet density, and penetration of spray. The paper is yellow and becomes blue when in contact with moisture (Figure 3.8).

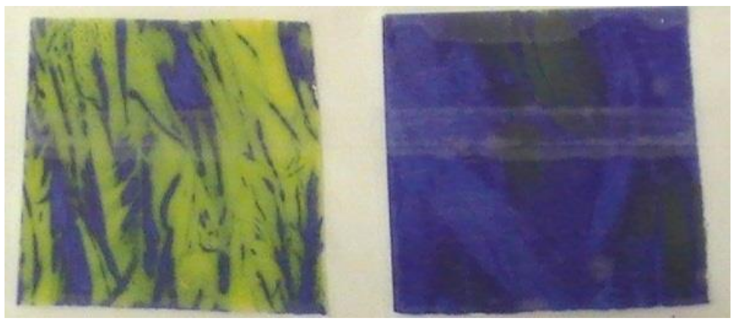


Figure 3.8 Two 2.5cm x 2.5cm pieces of moisture sensitive paper that were held to moist feathers

3.3.2.1 Device testing

Table 3.3 summarizes important characteristics of the devices and moisture paper used. For each feather density, measurements were taken from five separate areas on the swatch for each device/paper. The five areas tested were top left corner, top right corner, middle, bottom left corner and bottom right corner. Sensor portion of the sensors were placed on top of the feathers to receive a reading. Each of the five areas was additionally rotated 90 degrees three times resulting in a total of 20 readings per swatch per a device. In order to minimize feathers drying or evaporation of moisture, only one swatch was tested at a time and they were placed in sealed plastic bags when not in use. There were ten replications for each moisture level applied.

Table 3.3 Devices and material evaluated for feather moisture measurement in laboratory settings

Technique	Device	Original purpose	Characteristics	Price
Electrical Parameters	Decagon Leaf wetness sensor (Leaf sensor)	Leaf wetness Ice formation	Dielectric constant 320-1000mV @3V excitation	$187.93[1]
	Delmhorst FX-2000 (Hay sensor)	Moisture in hay bales	Conductivity 6-40% moisture	$ 590.63
	General MMH800 (Construction 1)	Moisture in building material	Conductivity 0-50% - wood - moisture 1.5 – 33% - other building material - moisture	$186.13
	Extech MO257 (Construction 2)	Moisture in building material	Capacitance 0-99.9% moisture	$252.99
	Extech MO265 (Construction 3)	Moisture in building material	Capacitance 0-100% moisture	$505.99
Insulative Ability	ThermaCAM™ S60 Infrared camera (IR camera)	Variety of uses	Measures emitted radiation from an object	>$22,000
Water Sensitive paper	Cobalt chloride moisture detection paper (Moisture paper 1)	Identification of leaks in roofs, car doors, between walls. Identification of spray or leakage patterns	Paper stains shades of red when in contact with moisture. Reversible reaction.	$4.18 per 8”x 10” sheet
	Teejet Spraying systems Co. paper (Moisture paper 2)	Evaluation of spray distributions, swath widths, droplet densities, penetration of spray	Paper stains blue when in contact with moisture. Permanent reaction	$72.00 per pkg of 50 3”x 2” sheets

[1] Additional costs ~$3000 for the data logger and software

3.3.2.2 Infrared Camera

The IR camera was installed on a tripod 1.5m from a metal water container on a hot plate. Water was maintained in the range of 39-42°C. The heated water container was used to mimic the body temperatures of broilers. Feather swatches were attached to the container using magnets and two images were acquired for analysis.

3.3.2.3 Moisture-sensitive paper

For this experiment, two types of moisture-sensitive papers were considered; Cobalt chloride moisture-detection paper from Indigo Instruments (Moisture paper 1) and Teejet water and oil-sensitive paper (Moisture paper 2). Moisture paper 1 was discontinued due to its ability to reverse the reaction when the paper was dried. The use of Moisture paper 2 caused discoloration of the feathers and had to be temporarily halted. It was tested later, after initial testing of the other devices was completed. Five pieces of 2.54 cm by 3.81 cm moisture-sensitive paper were placed against the conditioned swatch for ten seconds (same locations as the device testing).

3.3.2.4 Gravimetric moisture determination

For precautionary measures and to avoid excessive moisture evaporation, during testing, feather swatches were placed in sealable plastic bags when they were not being tested or being transferred from one location to another. Immediately following testing, the weight of the swatches and any bags used were recorded and the swatches were placed in a drying oven at 70°C for 2 hours. Post-drying weights of the dry swatches were recorded and the swatch was placed in a new plastic bag before conditioning it for the next moisture level. True moisture content of the feathers was determined using a simple gravimetric technique and equation 3.1.

$$Moisture\ \% = \left[\frac{wet\ feather\ weight - dry\ feather\ weight}{wet\ feather\ weight}\right] * 100 \qquad (3.1)$$

3.4 Statistical analysis

The mean of 20 values (for each daily moisture level from each device) was used in the analysis. The relationships between true moisture content and the device readings were studied using the GLM (general linear model) procedure of SAS 9.3 English (SAS Institute Inc., Cary, NC). The model used for the analysis was

$$Y = \mu + F + e \qquad (3.2)$$

where,

Y = the observation of the dependent variable (device reading),

μ = the population mean for the variable,

F = the effect of true moisture; as a fixed effect,

e = the random error associated with the observation.

Significance was declared when $P \leq 0.05$.

The MEANS procedure in SAS 9.3 was used for obtaining standard error values. The devices and moisture paper data were evaluated based on sensitivity, accuracy, and consistency of the devices. Feather density was not considered when making final conclusions, as it is not feasible to separate birds based on feather density in commercial barns.

Accuracy of the model created was evaluated using adjusted-R^2 values of the devices. Accuracy of the devices was compared using sum of squared error (SSE). Adequate sensitivity was determined using regression slopes of the devices. Lower slopes were considered to lack sensitivity and the ability to differentiate between moisture levels required for research purposes. For this experiment, higher slope values indicated a higher sensitivity of the device.

3.4.1 Infrared image analysis

A thermal imaging camera produces gray or colour-scale images that are made up of pixels (px) that represent individual temperatures (McCafferty, 2013). The IR images were uploaded into the Thermacam Quick Report thermal imaging program (FLIR Systems Inc. Burlington, ON). As the temperature gradient of the whole image includes the surroundings of the swatch, the swatch part of the image was defined using the selection tool. Individual pixel temperatures for a square area of 66px X 66px from the each of the five locations were recorded using a macro program in Microsoft excel. The macro sorted the data into five areas that were tested and generated average temperatures for each of the five areas. The average from each swatch were compared against the true moisture content to determine if any relationship was present using SAS 9.3 REG procedure. Significance was declared when $P \leq 0.05$.

3.4.2 Moisture sensitive paper image analysis

After exposing the papers to the feather swatches, they were scanned, using a colour scanner (x792de, Lexmark International, Inc., Lexington, KY), and digital images were stored in a computer. The settings used on the scanner were as follows: 600dpi (highest resolution available), colour scan, jpeg image file and sent via email. Using the Adobe Photoshop CS5 crop tool, a 2.5 cm x 2.5 cm area of the scanned image from the center was selected and extracted. Unwanted area and the background layers were deleted. Using the crop tool again the image was cropped to extract a smaller subsample with a manageable size (64px x 64px) for Matlab.

Using colour channels for red and green in Photoshop, pixel value thresholds were set to identify the amount of each image that appeared as “yellow”, “green”, “light blue”, and “dark blue” in individual images (Table 3.4).

Table 3.4 Ranges set using red and green colour channels to identify yellow, green, light blue, and dark blue pixels present in moisture-sensitive paper that had been exposed to the feather swatches.

Physical appearance of the pixels	Ranges of colour channels
Yellow	$200 \le \text{Red} \le 255$ and $200 \le \text{Green} \le 255$
Green	$\text{Red} \ge 118$ and $100 \le \text{Green} \le 200$; $118 \le \text{Red} < 200$ and $\text{Green} > 200$
Light blue	$0 \le \text{Red} \le 255$ and $60 \le \text{Green} < 100$; $118 > \text{Red}$ and $\text{Green} \ge 100$
Dark blue	$0 \le \text{Red} \le 255$ and $60 > \text{Green}$

A program created in Matlab was used for the final part of the moisture paper analysis. Based on the previously set ranges, the program in Matlab identified the number of yellow, green, light blue and dark blue pixels (out of total 4096 pixels) present in each image.

Half of the moisture paper 2 data were used as calibration data to develop a prediction equation. The GLM (General Linear Model) procedure and step-wise multiple regression in SAS 9.3 was used to analyze the data. The model used for the analyses was

$$Y = u + A*yl + B*gr + C*lb + D*db + e \qquad (3.3)$$

where,

Y = observation of the dependent variable,

u = population mean for the variable,

A, B, C, D = constant coefficients of the linear model, corresponding with yellow (yl), green (gr), light blue (lb), and dark blue (db) pixel counts, respectively, and

e = random error associated with the observation.

The prediction equations were used to validate the remaining half of the data. The relationship between predicted moisture and true moisture was studied using Proc REG in SAS 9.3. Significance was declared when $P \leq 0.05$.

3.5 Results and Discussion

All six devices indicated a significant relationship between device readings and true moisture content ($P<0.0001$). This was expected, as the original purpose of these devices was to detect moisture in various materials. In this study, the devices were evaluated using three main criteria: consistency, accuracy, and sensitivity. For all three criteria, feather density was not factored in the main analysis. One of the major challenges during this experiment was associated with the density of the feathers. All the devices and moisture paper 2 responded differently to varying levels of feather densities, regardless of the same moisture level treatment they received (Figures 3.9-3.15).

Wetness of feather swatches used in this experiment can be categorized into several levels: dry, dry with traces of moisture, wet, and drenched. Moisture content in each of these levels was based on true moisture determined via gravimetric technique. In order to be classified as dry, feathers should be mostly dry with very little moisture present (in the range of 0-5% true moisture). Wet swatches (true moisture 30-50%) would resemble a tea towel that was used on a heavy load of dishes. The second category of dry with traces of moisture is difficult to separate entirely from the surrounding categories and requires close attention. In terms of the tea towel analogy, this category would resemble a tea towel that has been used to dry few dishes. Typical field conditions of birds are in these first three categories. However, it is possible to recognize a fourth category, drenched, where feathers contain above 50% true moisture. This is a category that would be obvious to touch where birds would have free water within their feathers. Continuing the dishtowel analogy, the towel would have been dropped in a bucket of water and wrung. It is unlikely for this category to be present without it being an obvious welfare concern. Therefore, in addition to the above-mentioned four criteria, the ability of the device to measure moisture between 0 and 50% true moisture was also taken into consideration when evaluating the devices.

3.5.1 Leaf sensor

While the leaf wetness sensor did indicate a linear relationship ($P<0.05$) between device readings and the moisture content, upon further inspection it appeared to be better suited for a non-linear relation ($P<0.0001$).

Figure 3.9 compares the data gathered from the leaf sensor with the true moisture of the feathers. The graphical illustration of leaf sensor data illustrates only small differences between feather densities. However, numerically, slopes of each feather density treatment vary from one another. Additionally, depending on the moisture content, the slope of leaf sensor data differs, indicating that the sensitivity of the device is dependent on the moisture content. The high standard error value of the readings indicates that they are not consistent. The adjusted R-squared values indicate the majority of the variation in this device's measurements can be explained by the variation in the moisture held in feathers (Table 3.5). The SSE of the leaf sensor data is extremely high (Table 3.5). Typically this is an indicator of low accuracy of the device. However, it is important to recognize that the leaf sensor reading range (100-1000) is considerably higher than the other devices tested (0-100).

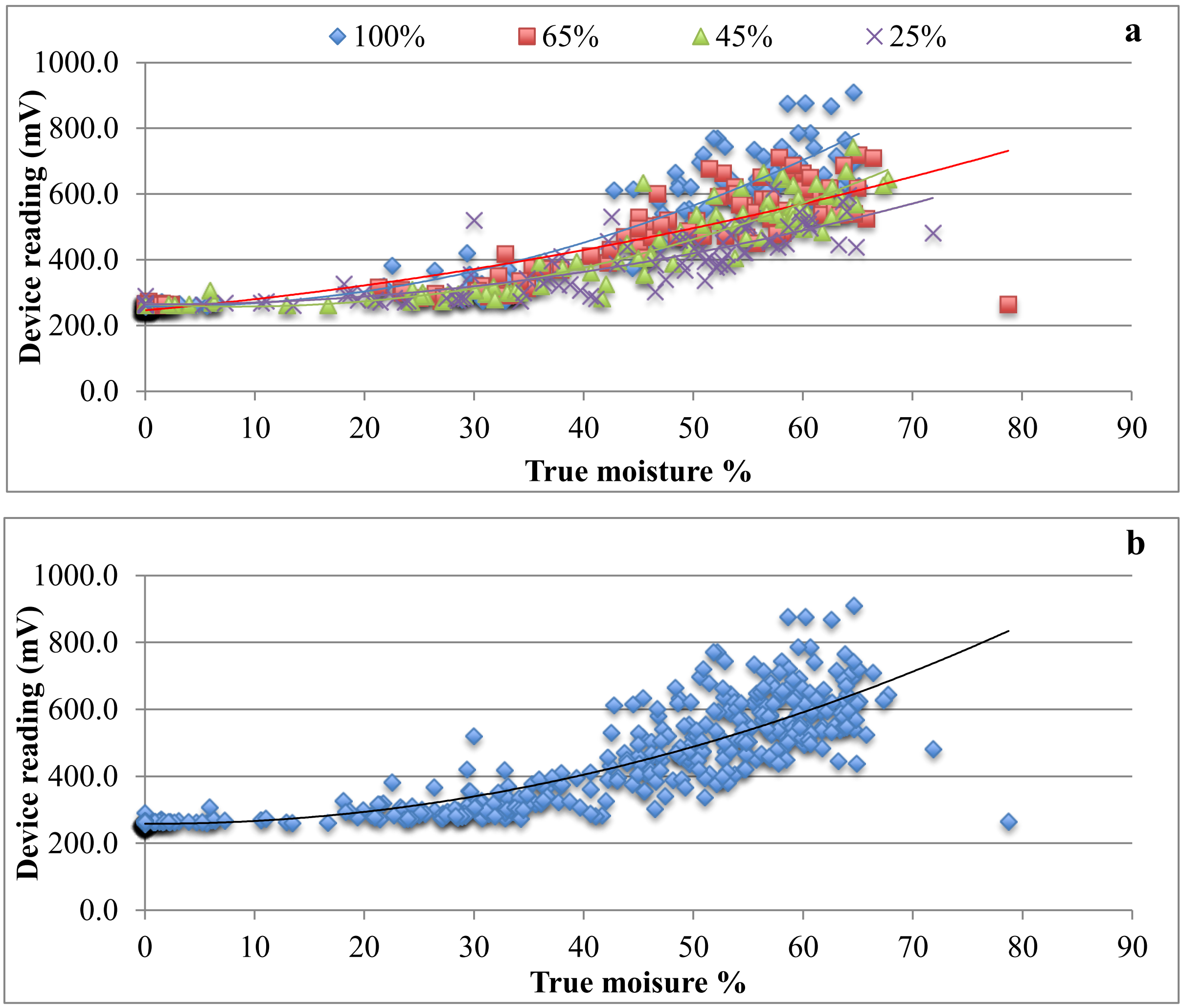


Figure 3.9 Comparison of device readings acquired from the leaf sensor and true moisture determined using gravimetric method (a) each density analyzed separately (b) feather density removed from analysis.

The leaf wetness sensor, originally designed to measure the presence and duration of moisture and ice formation on leaves, did not show potential to measure feather moisture, as it appeared to be incapable of differentiating when the moisture level was in the range of 0-40%. As typical field moisture conditions would be present between 0 and 50%, this device would not be suitable for detecting feather moisture.

Table 3.5 Comparison of tested devices based on sensitivity (slope), consistency (standard error), and accuracy (adjusted-R^2) using the results obtained from comparing true moisture content with device readings.

Device	Intercept (c)	a	b	P value	Adjusted R^2	Standard error	SSE
Construction 1	9.67	-*	0.63^{AB}	<0.0001	0.81^{A}	0.69^{CD}	36.45^{B}
Construction 2	12.32	-*	0.79^{A}	<0.0001	0.35^{D}	1.72^{B}	38.05^{B}
Construction 3	12.13	-*	0.68^{A}	<0.0001	0.52^{C}	1.03^{BC}	90.91^{B}
Hay sensor	12.28	-*	0.39^{B}	<0.0001	0.69^{AB}	0.46^{D}	51.51^{B}
Leaf sensor	273.64	0.10	0.11	<0.0001	0.66^{BC}	7.83^{A}	68669259^{A}
IR camera	26.10	-*	0.02^{C}	<0.0001	0.06^{E}	0.08^{E}	4.01^{B}

*Only linear relationships present between device readings and true moisture content, therefore no ‘a’.
Equation used: Predicted moisture = $ax^2 + bx + c$. The value for “x” was the mean meter reading.
^{A,B,C,D,E} Values within a column with different superscripts differ significantly ($P<0.05$)

3.5.2 Hay sensor

Although the true moisture exceeded 50%, the Hay sensor indicated its maximum reading when the feather moisture content was 45%. The inability of the Hay sensor to display readings above 45 percent should not be used as a limiting factor in field conditions, particularly because field conditions fall in the range of 0 - 50 %. Figure 3.10 indicates signs of the Hay sensor being affected by the density of the feather swatch. If the slope of the readings was the only factor to determine the suitability of this device to measure feather moisture, numerically, the hay sensor would be deemed as being not sensitive enough, indicated by the low slope value. However, statistically, the slope of the Hay sensor is not significantly different from the slope of Construction 1 (P>0.05). In addition, sensitivity was not the only factor used to evaluate the devices. Statistically, when feather density is not considered, the Hay sensor displayed the least variation (standard error) (not including IR camera results) amongst the data (Table 3.5).

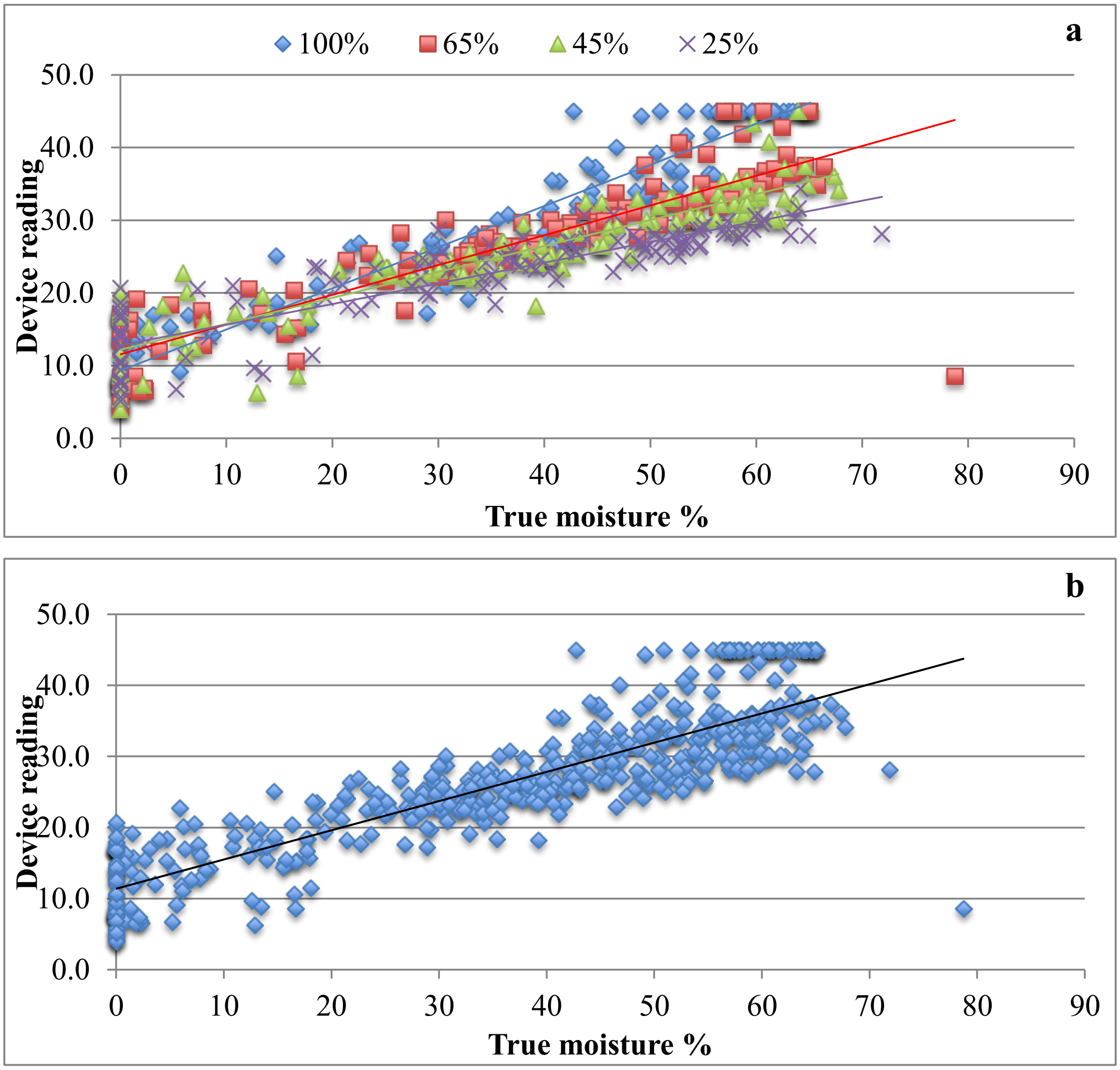
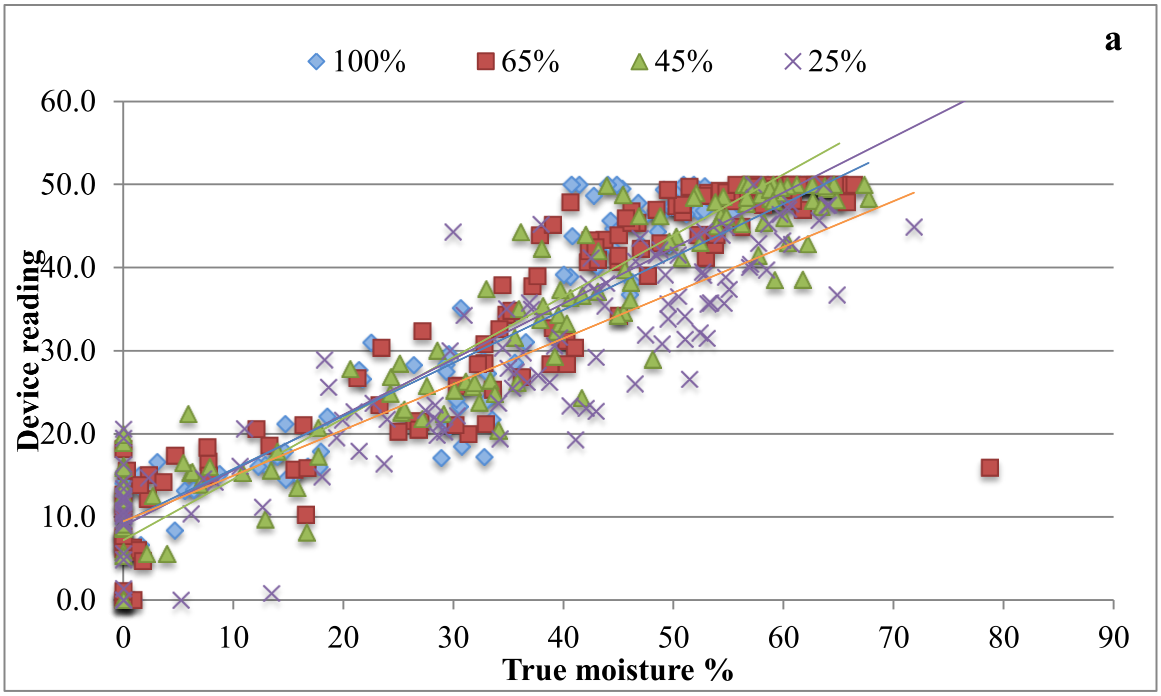


Figure 3.10 Comparison of device readings acquired from the hay sensor and true moisture determined using the gravimetric method (a) Each density analyzed separately (b) feather density removed from analysis.

3.5.3 Construction 1

The Construction 1 device, typically used to measure moisture levels in wood or other building material, also showed potential to measure feather moisture (Table 3.5). Similar to all the devices tested, Construction 1 indicated some inconsistency with feather densities (Figure 3.11). Construction 1 had better consistency than Construction 3, leaf sensor, and the IR camera ($P<0.05$), indicated by standard error values. Although Construction 1 had the lowest SSE numerical value, it was significantly different from only the Leaf sensor ($P>0.05$). According to the adjusted R-squared value obtained from Construction 1 data, the moisture held in the feathers can explain the large proportion of variability present. Construction 1 maintained the smallest range between slopes of the varying feather densities compared to other devices tested. This indicates that the strength of the relationship between device measurement and true moisture is very similar across different feather densities.



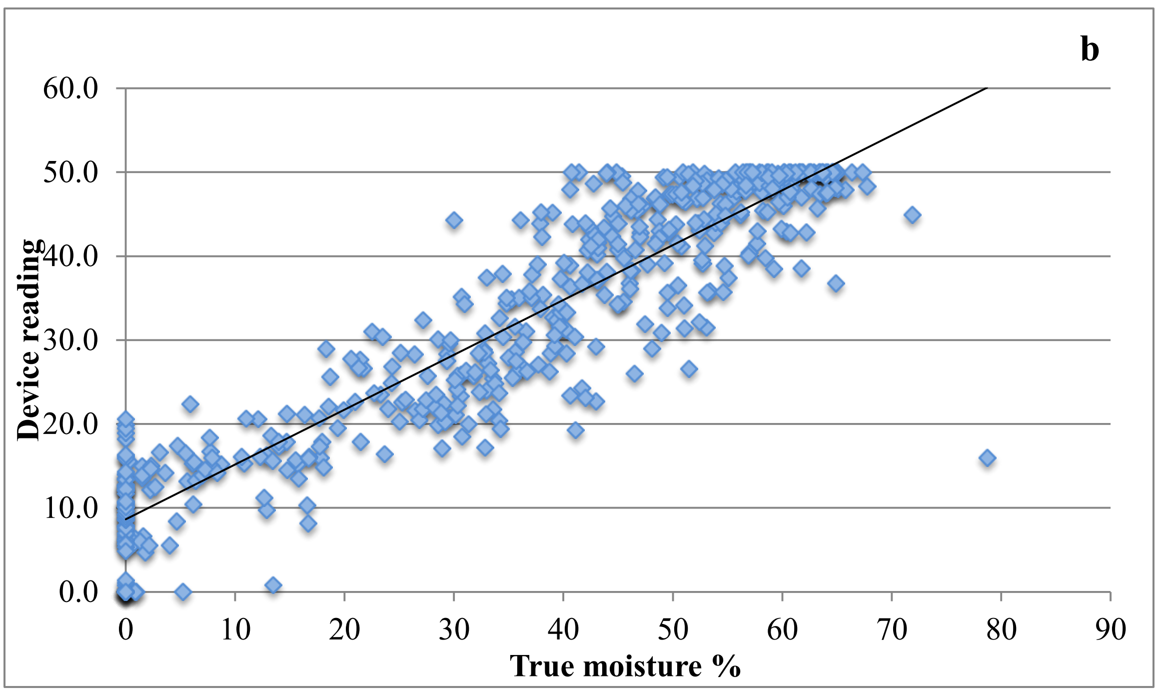
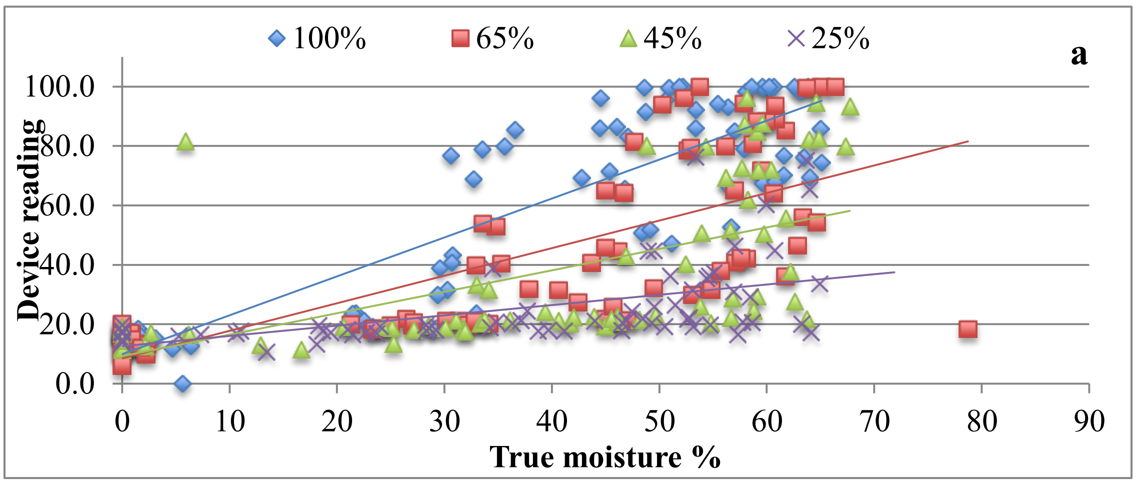


Figure 3.11 Comparison of device readings acquired from Construction 1 and true moisture determined using a gravimetric method (a) each density analyzed separately (b) feather density removed from analysis.

3.5.4 Construction 2

The Construction 2 sensor experienced malfunctioning issues during the trial and a new device was required. The data from the new and the old device were dissimilar and unpromising. The sensor was characterized as unreliable and was not considered any further. Figure 2.12 represents the data gathered from both devices and there is no clear pattern to be observed visually. According to the adjusted- R^2 value for Construction 2, only a small amount of variation within data is explainable by the model (Table 3.5).



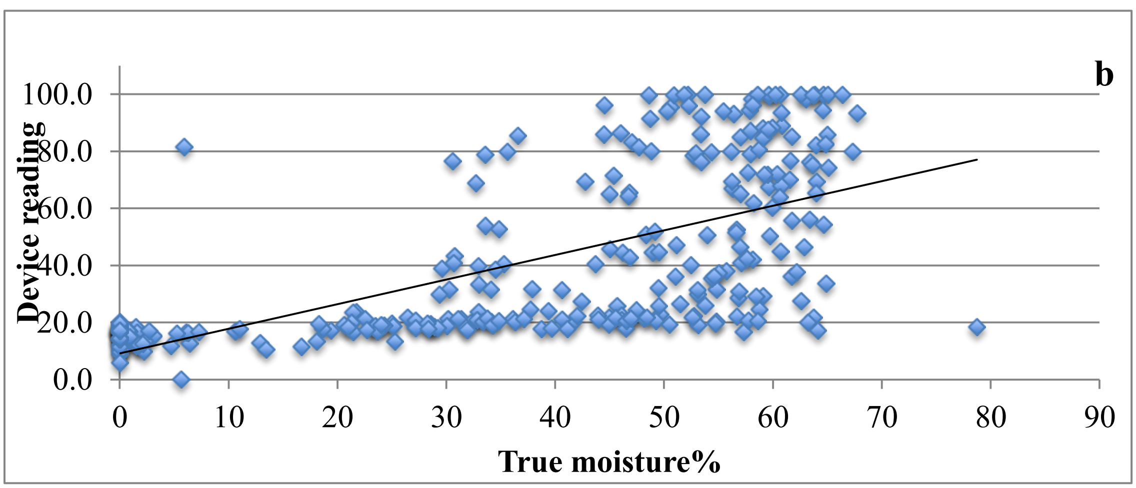


Figure 3.12 Comparison of device readings acquired from Construction 2 and true moisture determined using a gravimetric method (a) each density analyzed separately (b) feather density removed from the analysis.

3.5.5 Construction 3

Having an output range of 0-100%, it was felt that the Construction 3 meter would have been appropriate for field conditions. However, during data collection, the sensitivity to feather density was noted (Figure 3.13). While low-density swatches at different moisture levels always indicated as having low moisture content, any amount of moisture in high-density feathers produced a large moisture reading from the device. In terms of statistical values used to evaluate device suitability for field-testing, Construction 3 was in the middle of the ranking with slope, and adjusted-R^2 values but had undesirable high values for standard error and SSE (Table 3.5). Whereas this was the case numerically, when tested for significance, Construction 3 proved to be not significantly different from Construction 1 and 2 for slope, standard error, and SSE.

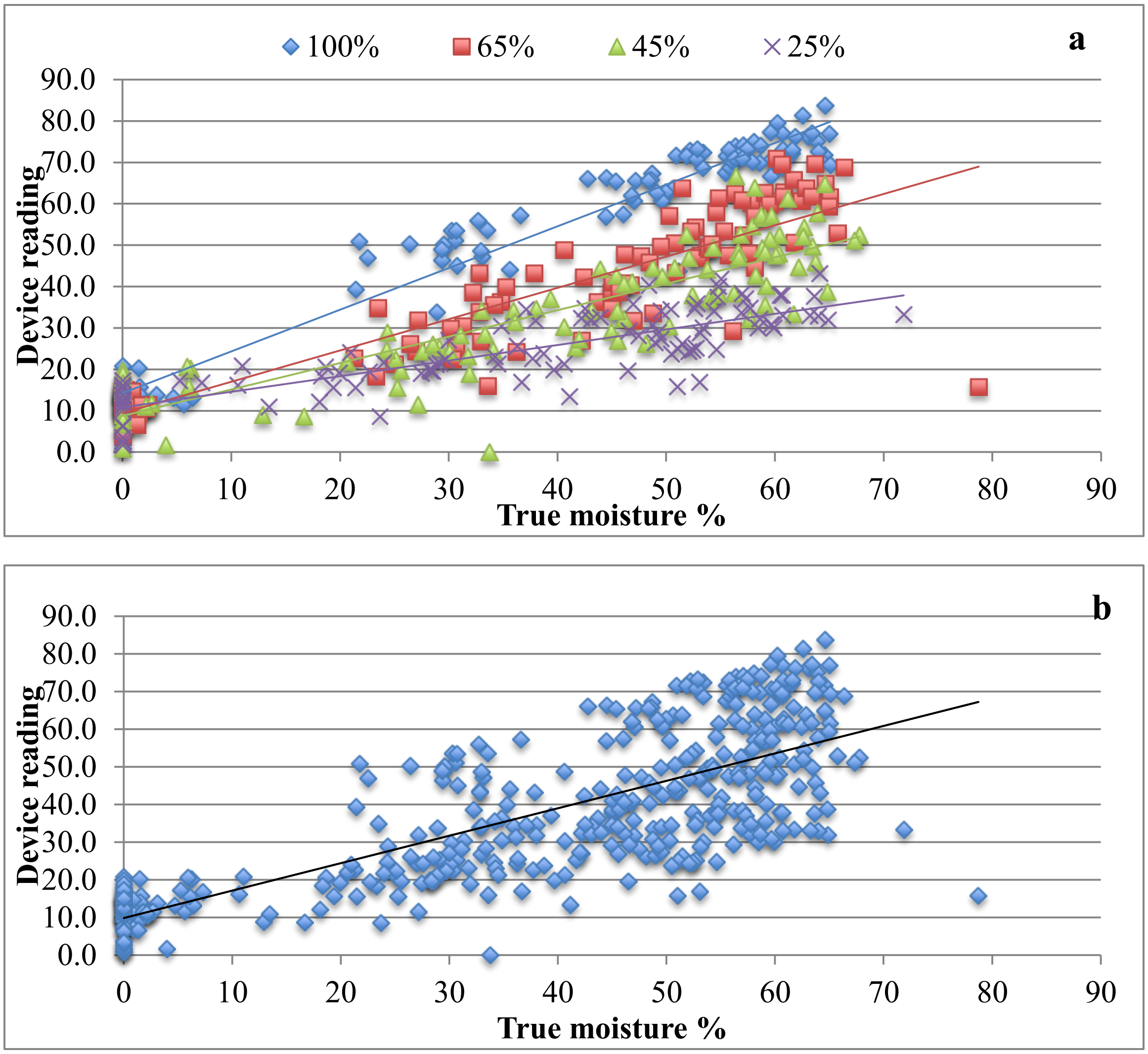
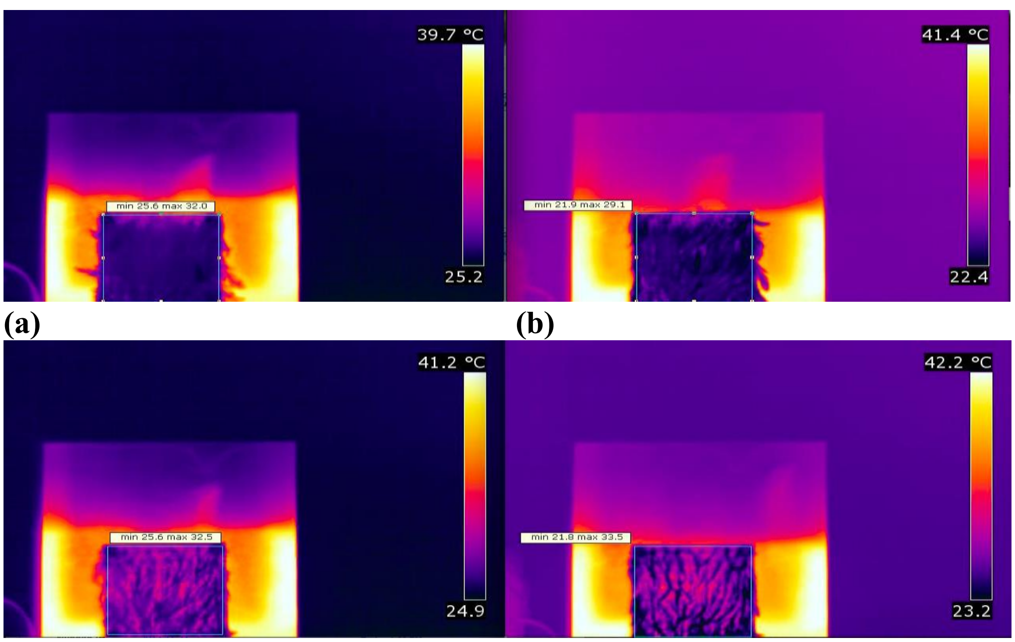


Figure 3.13 Comparison of device readings acquired from Construction 3 and true moisture determined using a gravimetric method (a) each density analyzed separately (b) feather density removed from the analysis.

3.5.6 Infrared camera

Thermal images obtained from the infrared camera were not in accordance with the predicted theory. It was expected that with more moisture in the feathers and/or lower feather densities, more radiation would be emitted and higher surface temperatures would result. Figure 3.14 shows the 100% (a & b) and 25% (c & d) density swatches respectively, with 0.0 (a & c) and 1.0 moisture levels (b & d) applied. From these images, the different temperature range is noticeable between moisture levels but not between feather densities. While there appears to be a significant relationship between true moisture content and the temperatures observed ($P<0.0001$), the near zero slope in the regression results indicate otherwise (Figure 3.15).

Overall, it appeared that the setup used to mimic live broilers to be a failure. It was believed that the plastic grids to which the feathers were attached was not allowing the heat to transfer through to the feathers. It has been speculated that this was due to the fact that the plastic grid has insulative capacity of its own and the heat exerted by the source was trapped between the grid and the source.



(a) **(b)** **(c)** **(d)**

Figure 3.14 Images from infrared camera displaying thermal gradients for a 100% (a & b) and 25% (c & d) feather density swatches at 0.0 (a & c) and 1.0 (b & d) moisture treatment levels applied.

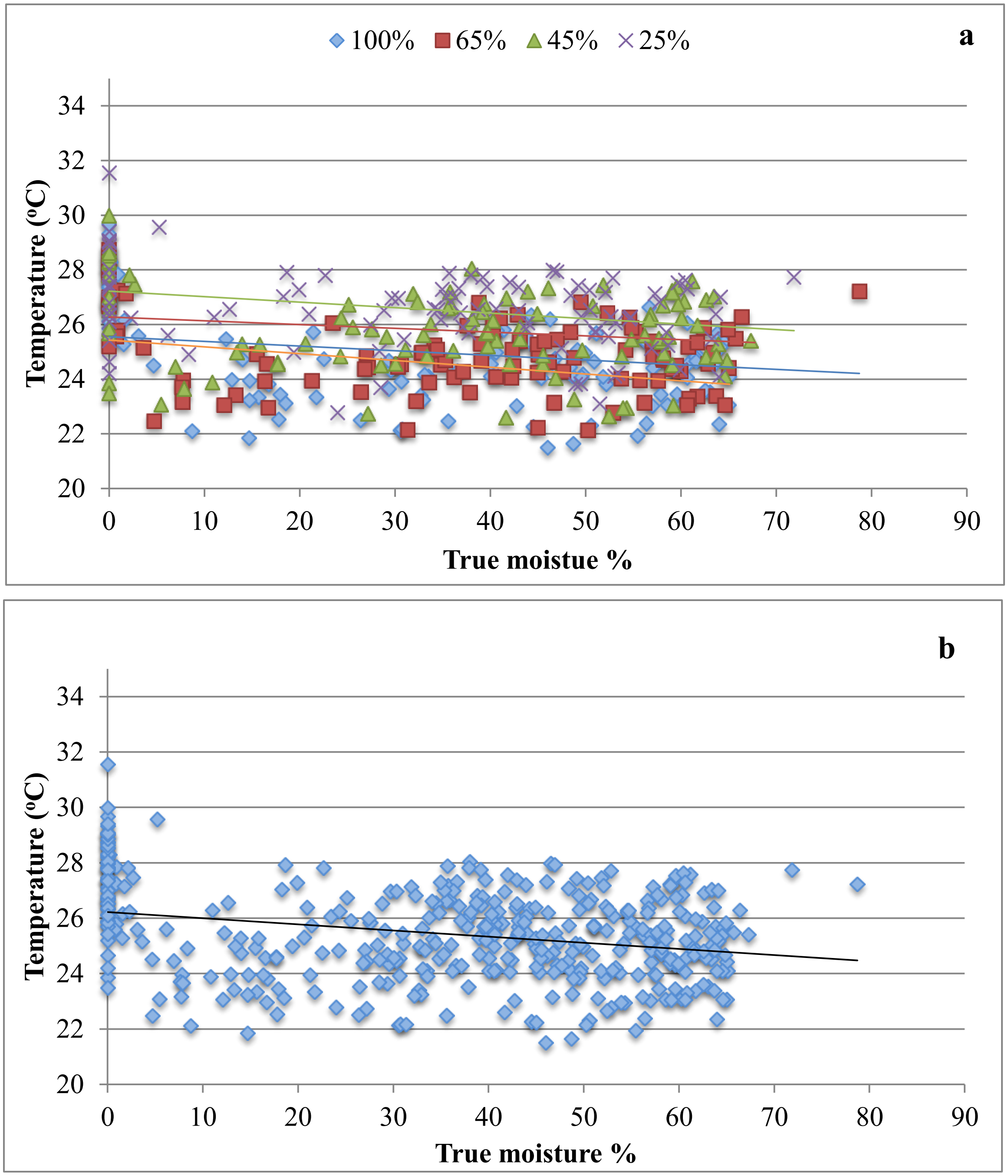


Figure 3.15 Comparison of temperature readings acquired from infrared camera images and true moisture determined using the gravimetric method (a) each density analyzed separately (b) feather density removed from analysis.

3.5.7 Moisture paper 2

Typically used for evaluation of spray distribution, spray swath widths, droplet densities, and penetration of moisture, Moisture paper 2 initially presented as a good product to use for feather moisture detection, as it appeared to be capable of differentiating between moisture levels. However, during the study it was noted that depending on the density of the feathers, the response of the paper differed, similar to other devices tested. It was noticed during analysis that a higher density of feathers resulted in a greater amount of moisture transferred to the paper. The number of feathers seems to affect the number of contact points between the swatch and paper (Figure 3.16).

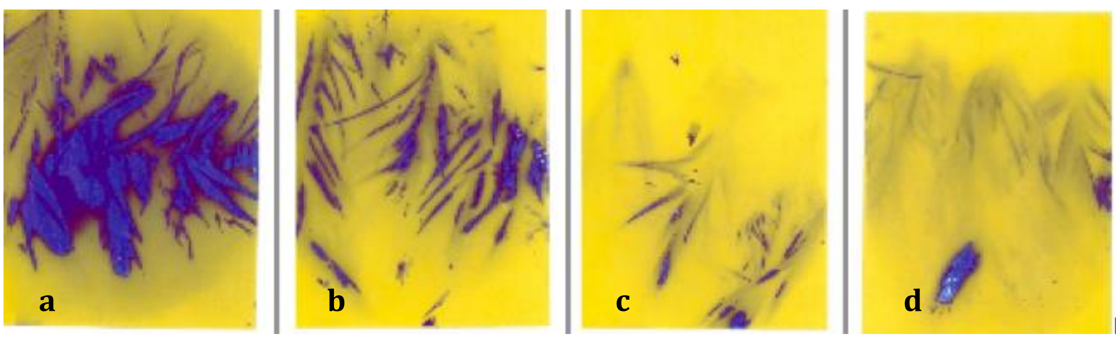


Figure 3.16 Scanned images of moisture-sensitive paper exposed to the 1.0 moisture treatment level with 100% (a), 65% (b), 45% (c), and 25% (d) feather density swatches.

Table 3.6 indicates the equations acquired from using calibration data for each of the moisture levels tested. These same equations were then used with validation data to obtain predicted moisture to compare against the true moisture values.

Table 3.6 The equation derived from calibration data compared to true moisture content and used in validation data set to predict moisture using moisture-sensitive paper.

Density (%)	Intercept (z)	A	B	C	D	P-value	Adjusted-R^2
100	77.7	-0.02	*	-0.01	*	<0.0001	0.76
65	68.1	-0.01	*	*	*	<0.0001	0.75
45	86.9	-0.02	*	-0.01	*	<0.0001	0.64
25	88.6	-0.02	*	*	*	<0.0001	0.47
All	80.1	-0.02	*	-0.91	*	<0.0001	0.65

A, B, C, D = constant coefficients associated with yellow, green, light blue, and dark blue pixel counts, respectively
*Not significant to be included in the equation (P>0.05)
Equation used: Predicted moisture = z + A*yellow + B* green + C*light blue + D* dark blue

In both calibration and validation data sets, there appeared to be a lack of sensitivity for ~0-20% moisture (Figure 3.17b & 3.18b). Using moisture paper, it may be possible to separate birds in the first two categories (dry and dry with traces of moisture) from wetter birds. For field testing, it is important that the device/product is able to monitor moisture in the 25-50% range and show an ability to differentiate between critical levels to identify whether a bird is suitable for transportation. It seems that for this experiment, moisture paper had limited sensitivity to moisture content, but more to the number of feathers available.

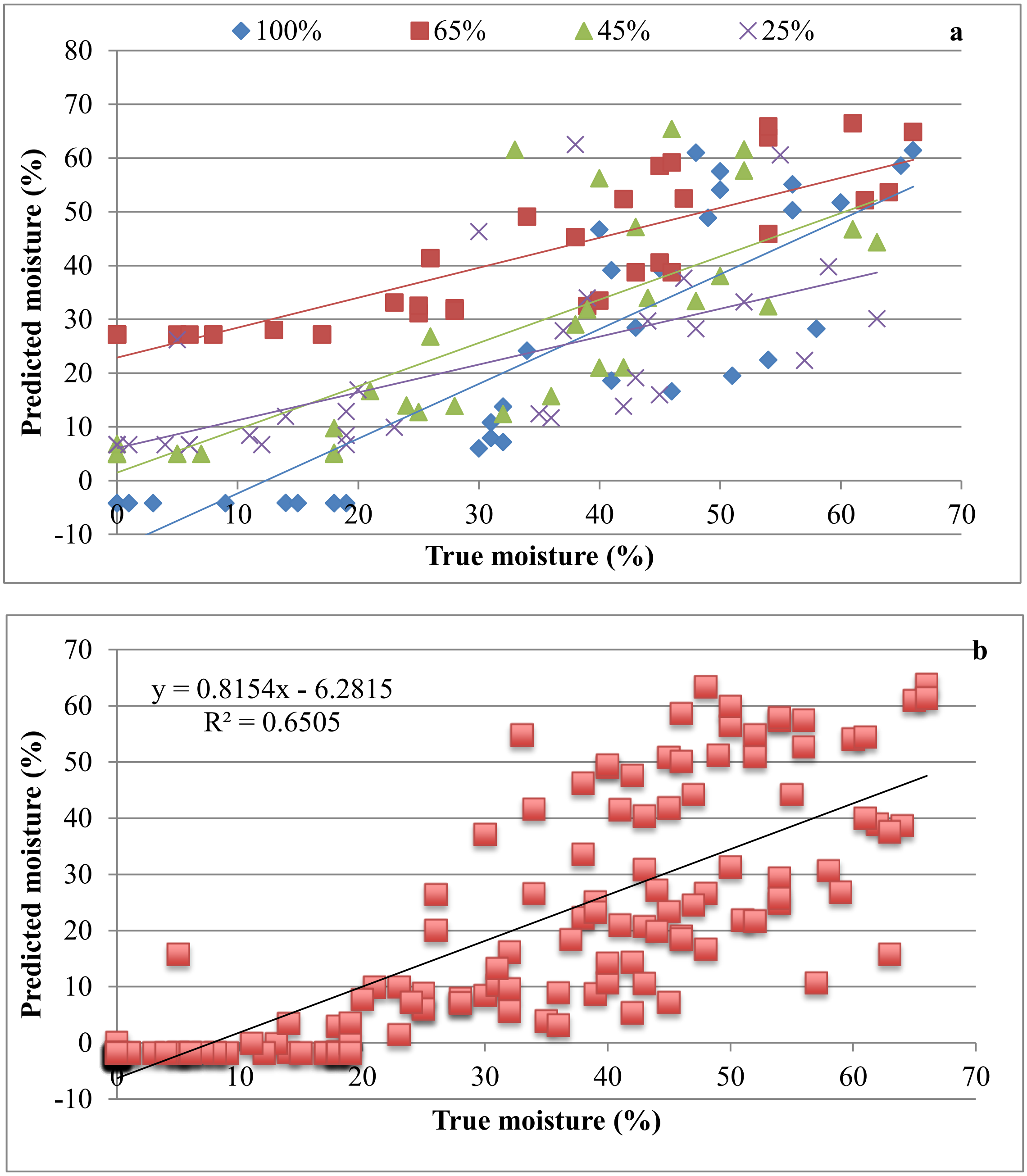


Figure 3.17 Comparison of predicted moisture data (using calibration data set of moisture paper) and true moisture obtained from gravimetric technique (a) Feather densities analyzed separately (b) Feather density not considered during analysis.

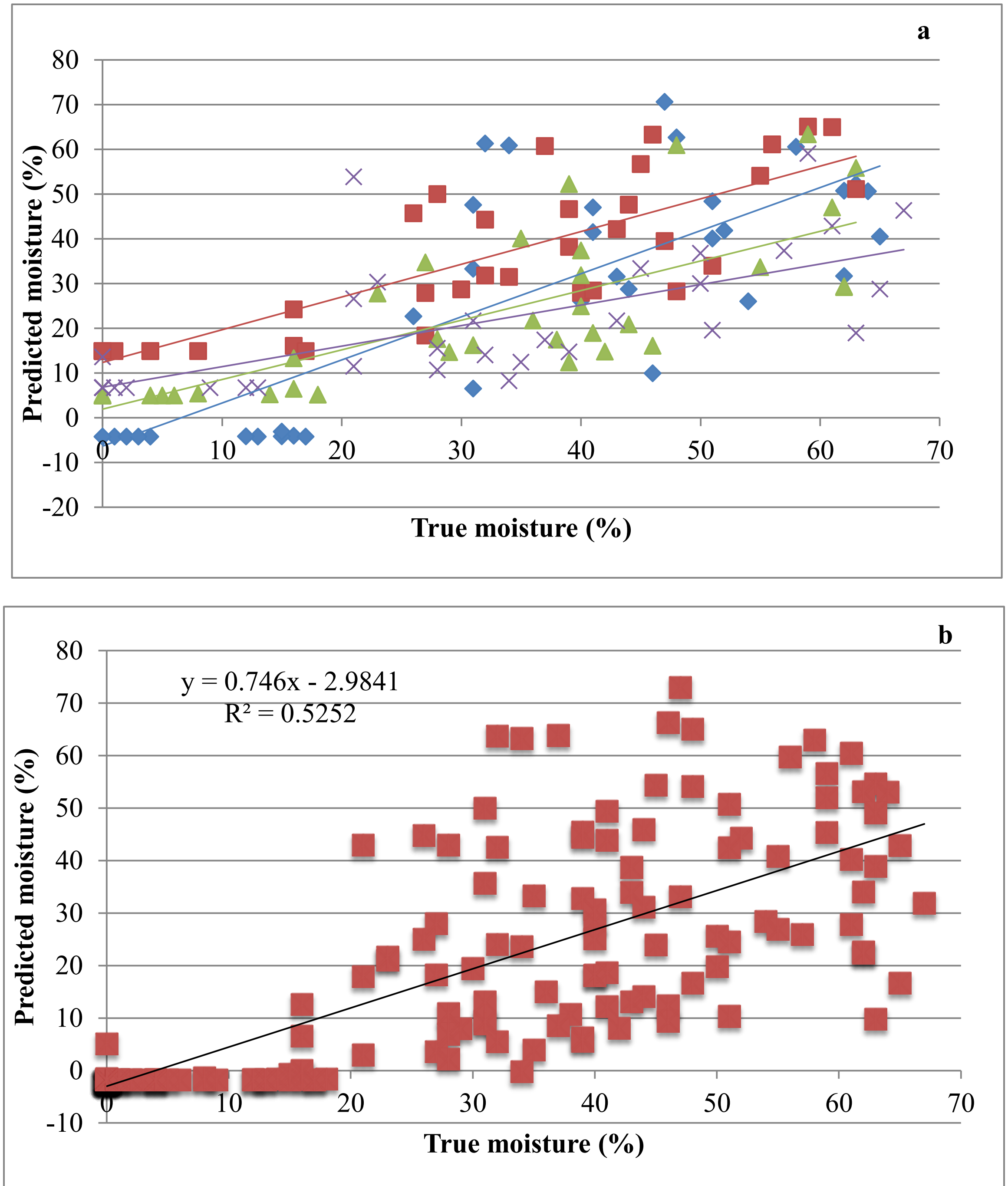


Figure 3.18 Comparison of predicted moisture (Validation data set of moisture paper) and true moisture obtained from gravimetric technique (a) Each feather density analyzed separately (b) Feather density not considered during analysis.

3.6 Conclusions

When selecting devices to use in the field, it is important to factor in field conditions. In addition to accuracy and sensitivity, consistency between feather densities and the potential range of device measurement are equally important factors to consider. From all the moisture levels that were tested, anything beyond the 1.0 treatment level (~40% true moisture) can be considered as an unlikely occurrence in field conditions. However, if such circumstances were to exist, it is believed that the birds would not be transported. Therefore a moisture meter that is capable of measuring up to 100% moisture but unable to differentiate between 15% and 30% true moisture would be unfit for further evaluations. From the above-discussed devices, the Hay sensor and Construction 1 were selected for evaluation at the field level. Although these two devices were not necessarily perfect, compared to the other devices, they showed the most promise in terms of the evaluation criteria for measuring moisture in feathers.

It is interesting to note that both devices selected occupy conductance as the technique to monitor moisture content. It is not possible to claim that devices using conductance for measuring moisture are more capable of monitoring feather moisture in comparison to capacitance or dielectric-constant-based devices.

Although not documented, there is a high possibility of differences existing between plucked feathers and feathers attached to living birds. Therefore, the recommended next step for this research would be to evaluate the devices using live birds.

Preface to Chapter 4.0: Evaluation of selected moisture sensors in field conditions.

The objective goal of this research was to determine whether available moisture-sensing devices were capable of measuring feather wetness of live market-age broilers. Hence, testing the devices on live birds in commercial conditions was a necessity. From the previous experiment conducted in a laboratory setting, the Hay sensor and the Construction 1 device were identified as the two devices that showed the most potential in monitoring feather moisture. As there are differences between live birds and the swatches created, these two devices were subjected to additional evaluation. In this chapter, data obtained from birds from three locations are analyzed and discussed.

4.0 EVALUATION OF SELECTED MOISTURE SENSORS IN FIELD CONDITIONS

4.1 Abstract

Two commercially available moisture-sensing devices were evaluated for their ability to measure moisture levels in feathers on live birds in commercial conditions. Devices were tested on market-age broilers from three different locations. At the University of Saskatchewan Poultry Centre, birds were wetted to test device capability to monitor moisture levels in feathers. Digital images of birds were taken to assign scores based on feather coverage and cleanliness. Two device readings were taken from each of the back feathers, wing feathers, and breast feathers, and a sample of feathers was collected from the back to determine true moisture content using a gravimetric technique. The shaft part of the feathers was removed to avoid internal moisture present in the feathers. Digital images indicated that the majority of the birds could be categorized as clean (79%) and well feathered (97%). Statistical analysis included SAS 9.3 regression analysis to define relationships present between true moisture and the device readings. The two devices were mainly evaluated based on their ability to produce consistent and accurate readings as well as show sensitivity to the change in moisture. While Hay sensor readings from all the locations and Construction 1 readings from back and wing locations were found to have a significant linear relationship ($P \leq 0.05$) with true determined moisture content of feathers, the two devices showed very little potential to measure feather moisture in terms of accuracy, sensitivity, and consistency. Contradictory to the previous experiment conducted in laboratory settings, evaluation of commercially available moisture-sensing

devices in commercial conditions indicated poor results in their ability to measure feather moisture.

4.2 Introduction

In Canada in 2013, over 600 million broilers were transported and slaughtered (AAFC, 2014). The same year, approximately 8.6 million birds were condemned at the slaughter plant, 1.7 million due to being dead on arrival (DOA). These values have remained similar over the past few years. Although not all, a portion of the DOA birds can be attributed to being wet birds prior to and becoming wet during transportation. When the number of DOAs for three western provinces (Alberta, Saskatchewan, and Manitoba) is examined based on each month, there is a trend to be observed (Figure 4.1). The DOAs during the colder part of the year (Oct-Mar) tend to be higher than the rest of the year. High DOAs in July can perhaps be explained by heat stress due to high environmental temperatures during that month. Figure 4.1 also compares the DOAs within western provinces with national levels of DOA birds. While both follow a similar pattern, it can be observed that the western provinces' DOA percentages tend to stay above national average DOAs for a majority of the months.

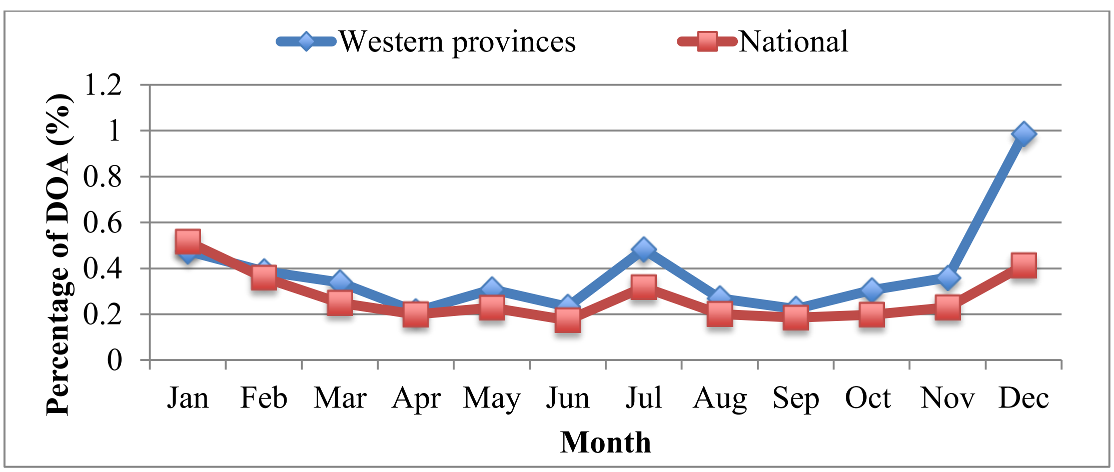


Figure 4.1 Percentage of DOAs observed monthly in 2013 (AAFC, 2014)

Temperatures across Canada can range from +40°C in the summer to below -40°C in the winter. It is impossible to avoid transportation of birds during colder temperatures due to the nature of the broiler industry. The rate of broiler growth and tightly scheduled production and processing operations minimize the opportunity of waiting for better weather conditions for transportation. Despite the efforts made by the broiler industry to ensure proper winter transportation, during colder months there tends to be a number of birds arriving dead.

Pre-slaughter on-farm conditions and transport conditions both influence the number of DOAs. Inadequate catching techniques can result in injuries to birds. Thomson et al., (2011) developed a decision tree that helped producers and catching crews identify birds that are and are not suitable for transportation. Recommendations included prevention of loading sick, injured as well as wet birds as they may contribute significantly to the number of DOAs. Recommendations by Thompson et al. are consistent with that of the Alberta Farm Animal Care Association (2007) and the Canadian Agri-Food Research Council (2003).

Previously conducted research has demonstrated the importance of providing appropriate transportation conditions in cold climates (Hunter et al., 1997; Hunter et al., 1999; Dadgar et al., 2010 & 2011; Knezacek et al., 2010; Strawford et al., 2011). As the numbers from AAFC (2014) indicate, there is an increase in condemnations during winter compared to summer. Without adequate ventilation and heat, birds often face poor welfare conditions in transit which in turn increase the number of DOAs (Hunter et al., 1999). Birds in transit are frequently in distress, suggesting that they are unable to maintain coping and adaptation mechanisms that permit them to return to a normal physiological and psychological state (Thomson et al., 2011). Taking distress into consideration, it becomes critical to be able to assure that only healthy birds are being loaded for transportation. Moisture accumulation during transport is a likely occurrence and therefore it is important that the plumage is dry prior to transportation.

While being wet cannot be used as an indicator for health, it is not a condition that should be overlooked. There is evidence indicating a positive relationship between wet birds and the number of DOAs in winter (Hunter et al., 1999). An experiment conducted by Hunter et al. (1997) suggested a relationship between the number of DOAs and the thermal environment of the transport vehicle. During winter transportation, the number of DOAs is higher in colder areas of the vehicle. Rectal temperatures measured indicated hypothermia as a potential cause for DOAs. The effects of cold exposure are particularly intensified if the birds are wet. Low air temperature and air movement, combined with wet feathers that can contribute to greater heat loss leading to rapid cooling of the birds (Hunter et al., 1997). In addition to increased DOA levels, hypothermia developed from cold and wet conditions can lead to increased incidences of meat quality defects along with higher shrinkage (Watts et al., 2011). Despite the industry acknowledging that birds with wet feathers are at risk and transportation of such animals should be prevented, it still occurs.

Wet birds can be a result of producers attempting to decrease production cost. In winter, producers decrease ventilation rates to decrease their heating costs (Hall and Menges, 2012). Although there is substantial cost benefit in decreasing ventilation rates, it may also have negative consequences such as accumulation of moisture in the barn that is absorbed by broiler feathers, resulting in wet birds. Assessing the suitability of birds for transportation is the responsibility of the driver. Even with adequate common knowledge, it is still difficult to quantify bird wetness without a scientific method or a device to measure moisture and justify preventing wet birds from being transported.

Previous experiments conducted under lab settings indicated potential to measure feather moisture using commercially available moisture sensors initially designed for use with other material. The two selected devices were originally designed to measure building material (Construction 1) and hay (Hay sensor) moisture. Both devices use conductivity as a means to predict the moisture content. Conductivity is the ability of a material to conduct an electrical current. In order to determine the conductivity, the sensors apply an electric potential and the current that passes through the material is measured. As the moisture content increases, more current will pass through the material.

In addition to moisture level, electrical conductivity can also be affected by a number of other characteristics. In soil, it is affected by soil structure, soil temperature, contact between the material and the sensor, and type and quantity of minerals in soil and water (Hartsock et al., 2000). A similar concept can be applied when measuring feather moisture conductivity. There is likely a significant difference in substrate present between feathers attached to the birds versus plucked and cleaned feathers. Testing moisture-sensing devices, using plucked feathers, is groundwork for evaluating their ability to measure feather moisture. However, it is important to also test the devices using live birds in order to account for the different characteristics that may influence the conductivity and the moisture reading provided by a device.

The objective of this experiment was to evaluate the moisture-sensing capabilities of devices selected from previous experiments using live broilers in various commercial settings.

4.3 Experimental Design

The University of Saskatchewan (U of S) Animal Care Committee approved all the research protocols used according to the recommendations of the Canadian Council of Animal Care.

Research was conducted at a commercial broiler barn located outside of Saskatoon, a commercial processing plant in Saskatchewan, and the U of S Poultry Centre between November 2013 and July 2014. Two of the seven devices/products tested in laboratory testing (Chapter 3) were selected for evaluation (table 4.1).

Table 4.1 Devices evaluated for feather moisture measurement in field settings

Technique	Device	Original purpose	Characteristics	Price
Electrical parameters	Delmhorst FX-2000 (Hay sensor)	Moisture in hay bales	Conductivity 6-40% moisture reading	\$590.63
	General MMH800 (Construction 1)	Moisture in building material	Conductivity 0-50% - wood moisture reading 1.5 – 33% - other building material reading	\$186.13

4.3.1 Commercial barn testing

At the commercial broiler barn, a group of Ross 308 birds (N=25) (13 males and 12 females) aged 33 d (average weight 1.83kg) were tested from different locations of the barn three days prior to load out. Five general areas were selected in an attempt to account for the range of moisture that may be present at different locations in the barn.

Birds were selected from under a fan, in between two fans, in front of the overhead door, near the resting area (away from feeders and drinkers) and near the feeders and drinkers. Measurements were collected from two separate zones for each location (both sides of the barn).

4.3.2 Processing plant testing

A Sofina processing plant located in Wynyard, SK, approximately 200 km southeast of Saskatoon was the second location used in this experiment. Birds were tested close to their arrival time at the plant. To account for moisture levels at different locations of the transport vehicle, measurements were collected, using birds transported at the:

1) rear of the trailer, bottom module,
2) middle of the trailer, top module and
3) front of the trailer, top module.

In order to avoid fecal contamination, birds were randomly selected only from the top two drawers of the modules. A total of 288 Ross 308 broilers aged between 34 and 38 d (133 males and 157 females; average weight 2.08kg) were tested at the processing plant.

4.3.3 University of Saskatchewan Poultry Centre testing

The final part of the trial took place at the U of S Poultry Centre where a group of Ross 308 birds were placed into a single floor pen (N=60) (average weight 2.14kg). All the birds were tested once at the age of 33 d, then again at 34 d. Feed and water were available ad libitum.

Birds were wetted individually by placing each bird in a tub containing lukewarm water. In order to avoid contamination, fresh water was used for each bird. Birds were held in the water for approximately 10 seconds, ensuring that the base of the neck stayed above the water. While in water, the back feathers were lifted to saturate feathers. After wetting the feathers, birds were placed in an area in the pen separated by netted dividers approximately for 20 minutes to allow excess water to be shaken off and evaporate. Birds were tested in the same order they were wetted.

Each bird was tested twice on two separate days and a sample of back feathers was plucked from each bird each day. Precaution was taken to ensure the sampling/testing locations on each bird were different for the two days.

4.3.4 Data collection

4.3.4.1 Individual bird information

Each bird was tested individually and only once at the commercial farm and the processing plant. At the U of S research facility, each bird was tested twice on two separate days. Body weights were obtained using a hanging scale suspended from a tripod.

Duplicate infrared and digital images of the dorsal plane of the bird were captured while the bird's legs were held and it rested its breast on the table surface. Digital images were used to assess the feather coverage and the cleanliness of the feathers consistent with Tauson et al. (2005) and RSPC (2011) (Table 4.2 and 4.3). The purpose of the infrared images was to monitor the surface body temperature of the broilers.

Table 4.2 Description and images of each subjective feather coverage score for the breast, wing, and back (images from Tauson et al., 2005)

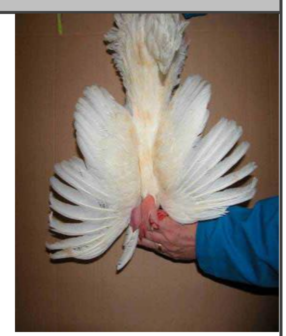
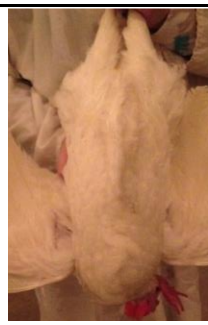
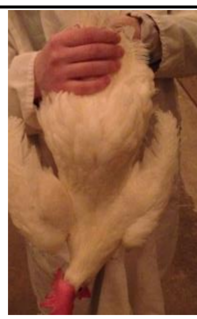
	Subjective Feather Coverage Score			
	1	**2**	**3**	**4**
Description	Surface is completely bare	Significant (>10%) portion of the skin is bare	Small to moderate portion (<10%) of the skin is bare	Surface completely covered in feathers
Breast				
Wing				
Back				

Table 4.3 Description and images of each subjective feather wetness and dirtiness score for the breast and back feathers (images from RSPCA, 2011)

	Subjective Feather Wetness and Dirtiness Score			
	0	**1**	**2**	**3**
Description	Clean and feathers are dry to the touch	Lightly soiled and feathers will be slightly matted due to moisture	Medium soiling and the feathers are matted due to moisture	Heavy soiling and the feathers are laden with moisture causing extreme matting
Breast				
Back				

Next, feather moisture measurements were taken using the two selected devices (Construction 1 and Hay sensor) from three specific locations of the bird (Figure 4.2):

1. feathers covering the spinal tract (*pterylae spinales),*
2. feathers on the outside of the wings (*tectices marginales superiores prepatagii)* and
3. breast feathers (*pteryla sternalis).*

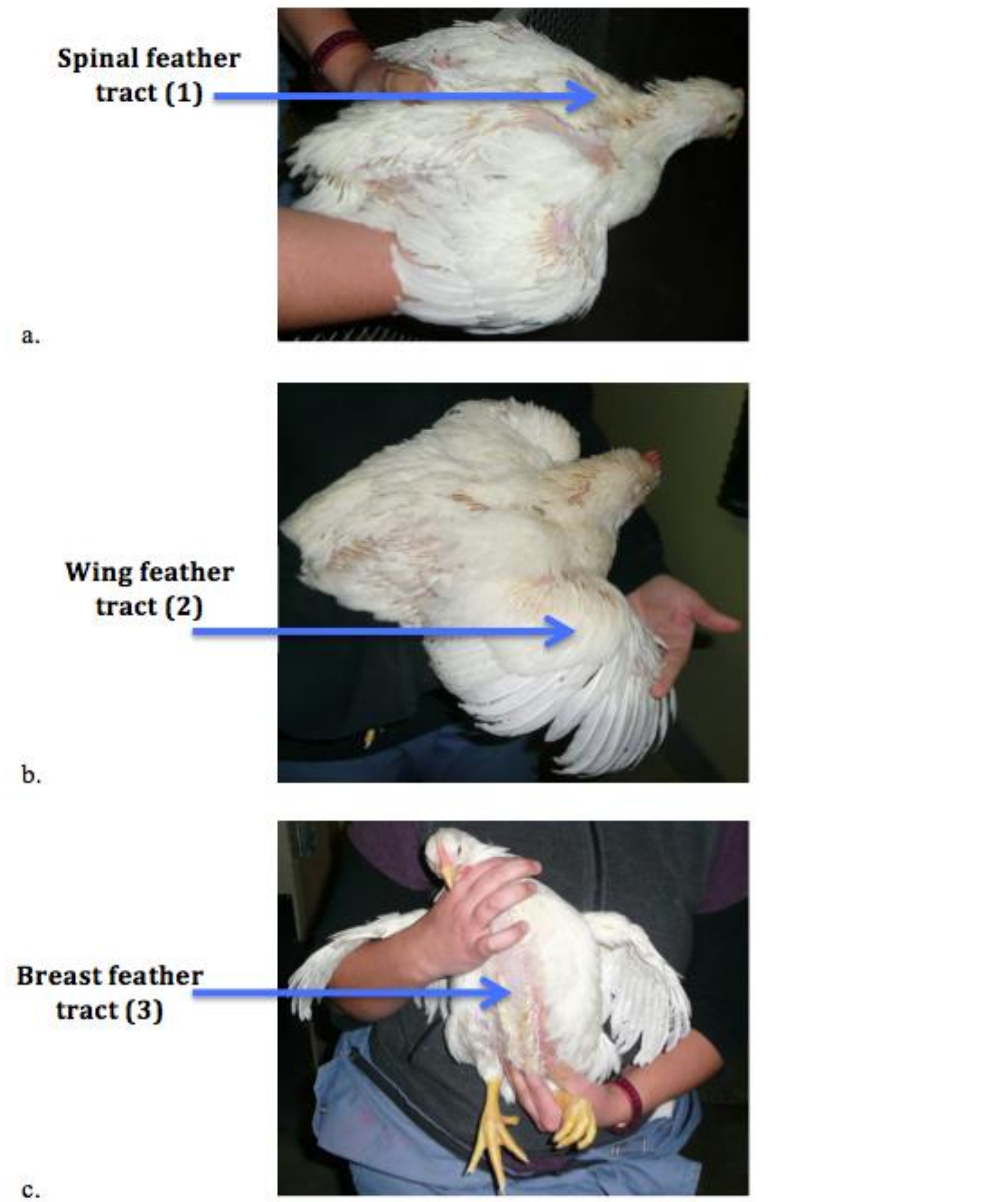


Figure 4.2 Example images of the feather tracts where moisture measurement were taken

These three locations can be considered as three important feathered areas covering the majority of the body and providing insulation to the bird and were selected for acquiring readings. In addition, these three areas have the potential to get wet and dirty under varying situations.

4.3.4.2 Feather sampling

From each of the birds, a sample of back feathers (~1.5cm^2) was extracted by pulling. The samples were placed in individual sealable plastic bags and transported to the university lab at the end of testing. The shafts were removed as close to the base by cutting to eliminate any blood or additional moisture present. They were placed in the oven for 2 hours at 70^0C. The gravimetric technique was used to determine the moisture content of feather samples.

4.4 Statistical analysis

Similar statistical analysis procedures as described in Chapter 3) were conducted for the analysis of data obtained from Construction 1 and Hay sensor. Primary analysis included all the data without factoring testing location. The relationships (both linear and quadratic) between device readings and true moisture were studied using Procedure GLM in SAS 9.3. Each body location (back, wing, and breast readings) was analyzed separately. Sum of squared error, and standard error in the MEANS procedure and slope and adjusted R^2 value from Proc REG were used to study sensitivity, accuracy and consistency of the devices. Tukey's Studentized Range Test was used to separate means and see whether the readings for the two devices significantly differed for each body location, with a probability of difference level set at 0.05.

A secondary analysis was also conducted, identical to the above mentioned, for each location (commercial barn, Poultry Centre, and processing plant) tested. Significance was declared when $P \leq 0.05$.

4.5 Results and discussion

Identical to laboratory testing, consistency, accuracy, and sensitivity were identified as criteria to evaluate the devices. Adjusted R^2 values and sum of square error (SSE) were used to evaluate the accuracy. While adj-R^2 describes the amount of variability of the data that is explainable by the model, SSE would, ideally, indicate whether the data provided by the device are accurate, similar to the true value. Use of SSE values for evaluation of device accuracy was challenging in laboratory testing due to the large variability in reading ranges between devices. This is not as much of an issue for the current research; as the two devices used both occupy similar ranges of readings (Table 4.1).

Sensitivity of the devices was determined by comparing the regression slopes. Mathematically, slope is a quotient, the change in output (device reading) divided by the change in input (true moisture). Higher slope values are preferred for this research, as that would signify the device being capable of differentiating between critical moisture levels. Laboratory testing indicated Construction 1 (0.63) to have better sensitivity (higher regression slope) than the Hay sensor (0.39). Consistency was evaluated using SE values. A smaller SE would denote more reliable, consistent results. Both devices, the Hay sensor and Construction 1, demonstrated capability in providing consistent results by small SE values (0.69 and 0.46 respectively) compared to other devices tested in the laboratory phase.

For both devices, data from the back and wing locations showed a significant relationship between device readings and the true moisture content ($P<0.0001$). Readings acquired from breast feathers using Construction 1 also indicated a significant relationship between the readings and the true moisture (P=0.0119). It was possible that a non-significant relationship might exist between true moisture and readings obtained from wing and breast feathers, as the sample feathers used to determine true moisture were taken from the back. Similar to chapter 3, devices were analyzed based on their ability to produce accurate, consistent results as well as the sensitivity of the device. Back feather data were used for evaluation in this paper.

4.5.1 Feather coverage and cleanliness scores

A majority (~97%) of the tested birds was identified as well feathered (back feather coverage scores 3 & 4) (figure 4.3a). Similarly, feather cleanliness scores indicated that the majority (~79%) of the tested birds as clean (score 1 & 2) (Figure 4.3b). With these results, it was assumed that the feather coverage did not have a significant impact on device readings. It should be noted that in a majority, if not all, of the birds, there were very few breast feathers present. It is likely that the measurement taken as breast feather moisture was recorded with the device in contact with the skin in the breast muscle area.

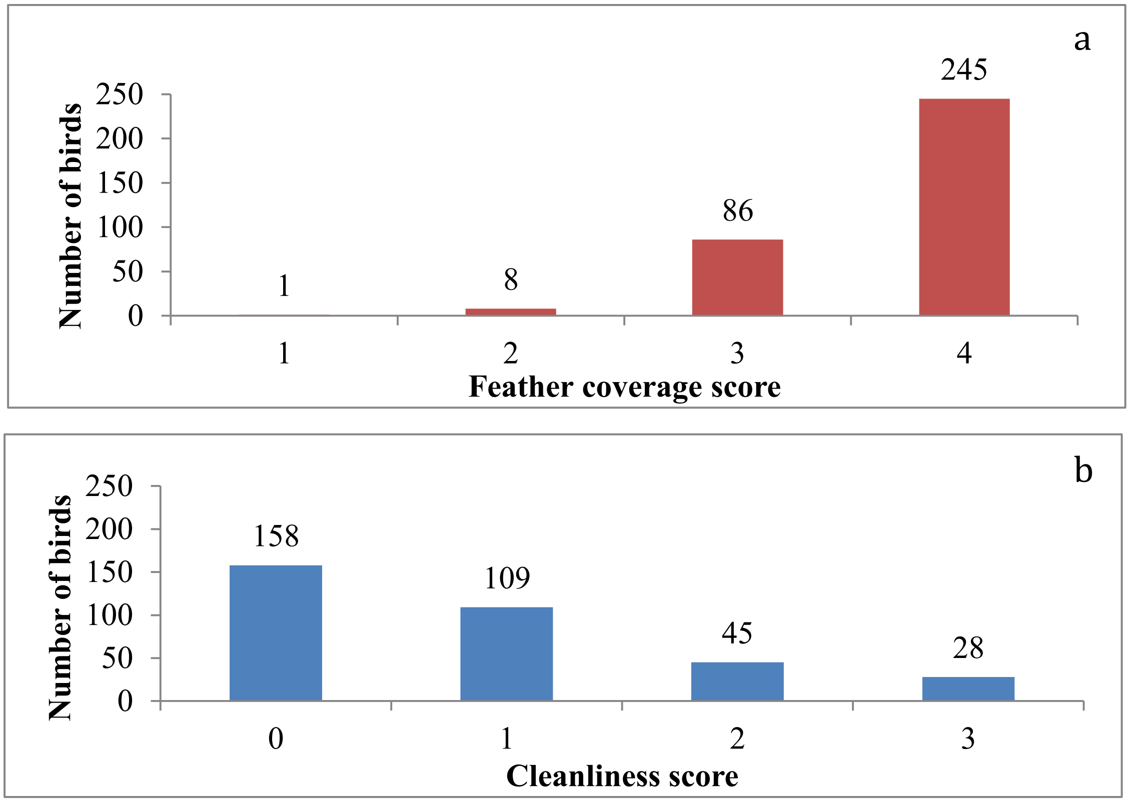


Figure 4.3 Number of birds in each score of feather coverage (a) and cleanliness (b)

4.5.2 Hay sensor

Figure 4.4 illustrates the relationship between data gathered using the Hay sensor and true moisture during field-testing. While results indicated a significant statistical relationship between true moisture content and the readings attained from all three locations ($P<0.05$), when the criteria for evaluation are considered, it has very little meaning. In terms of sensitivity, back and wing location data were similar (Table 4.4). The low slopes indicated that the changes in output (device readings) were much smaller than the change in input, true moisture. This was similar to laboratory results where Hay sensor had a relatively small slope value in comparison to the other devices.

It is clear from adj-R^2 values that the model accounts for very little of the variation in data. This is also observable in figure 4.4 by the scattering of data in each of the graphs. The SSE value for back feather readings from Hay sensor was notably smaller than the Construction 1 SSE value. As mentioned in the previous chapter, it is difficult to compare SSE values as the range of device readings have an effect on the resultant value. However in this case, both devices occupy similar ranges (Hay sensor: 6-45% and Construction 1: 0-50%). With a smaller SSE value, Hay sensor can be identified as the device capable of providing more accurate readings compared to Construction 1.

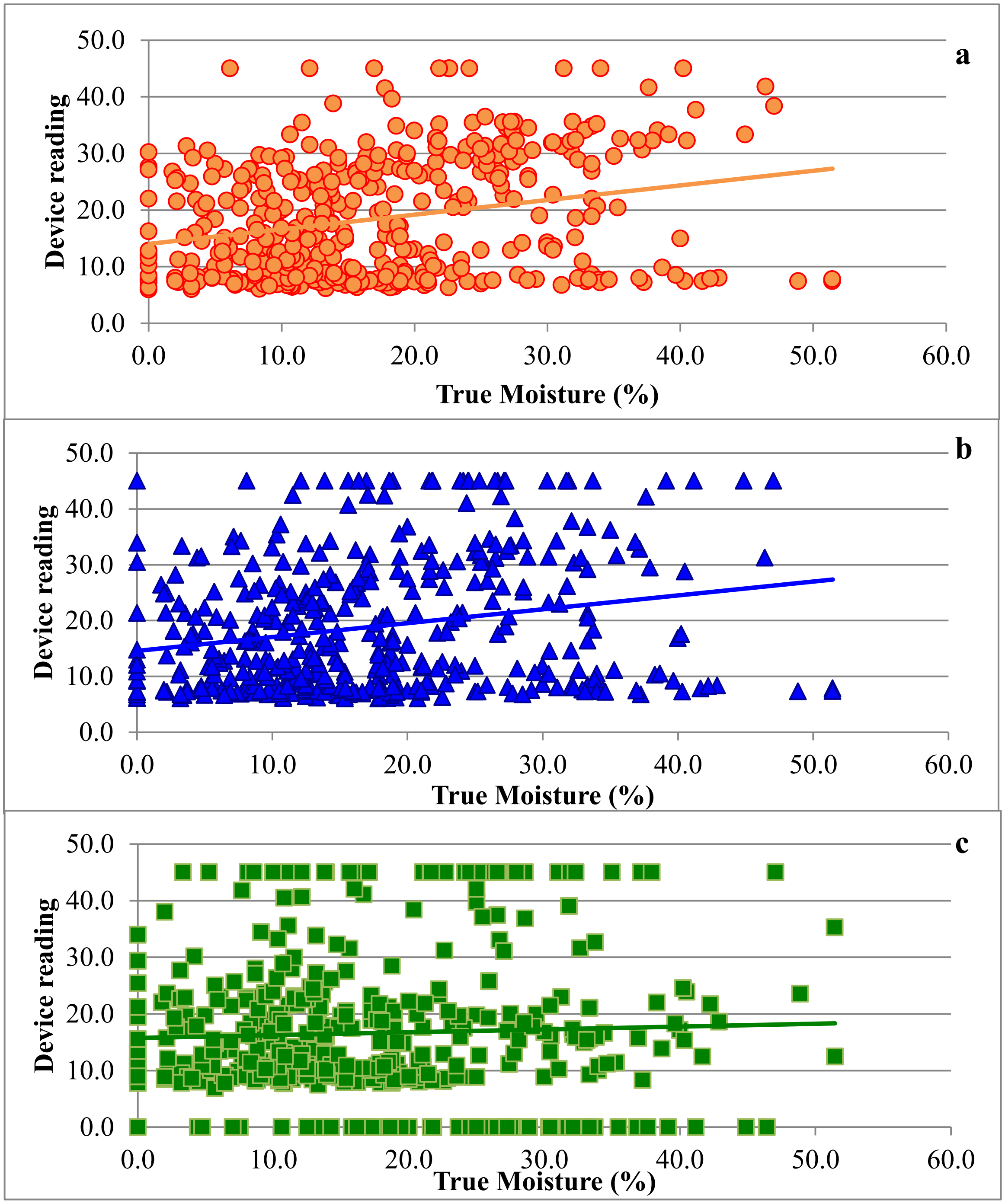


Figure 4.4 Comparison of back (a), wing (b), and breast (c) feather data gathered using Hay sensor during field testing and true moisture determined by the gravimetric technique.

Table 4.4 Results obtained from comparing true moisture content with the two device readings at three different locations of the body (back, wing, and breast)

Device	Location	Intercept (z)	b	Adjusted-R^2	P-value	SE	SSE
Hay sensor	Back[A]	13.70	0.27	0.07	<0.0001	0.50	57.22
	Wing	14.06	0.26	0.05	<0.0001	0.57	76.63
	Breast[A]	13.90	0.07	0.01	0.0521	0.39	130.67
Construction 1	Back[B]	6.62	0.52	0.15	<0.0001	0.69	47.35
	Wing	8.99	0.50	0.09	<0.0001	0.84	75.78
	Breast[B]	10.54	0.11	0.02	0.0119	0.45	176.42

Equation used: Predicted moisture = bx +z ; b=slope of the device readings, x=device reading
[A,B] Significant differences between two devices ($P<0.05$)

4.5.3 Construction 1

In comparison to the Hay sensor, Construction 1 shows better-quality results in terms of sensitivity and the accuracy of the model created (Table 4.4). These results follow a similar pattern as laboratory results. However, these values still are not sufficiently promising to say that the device is reliable for measuring feather moisture content. Similar to the Hay sensor, data from Construction 1 are scattered and do not reveal a consistent relationship with feather moisture content (Figure 4.5). In addition a high sum of square error for all three locations combined with low adjusted R^2 values indicate that the accuracy of the device is questionable. If consistency of the device were the only criteria to be evaluated, slightly lower SE values for Construction 1 would indicate it was superior to the Hay sensor.

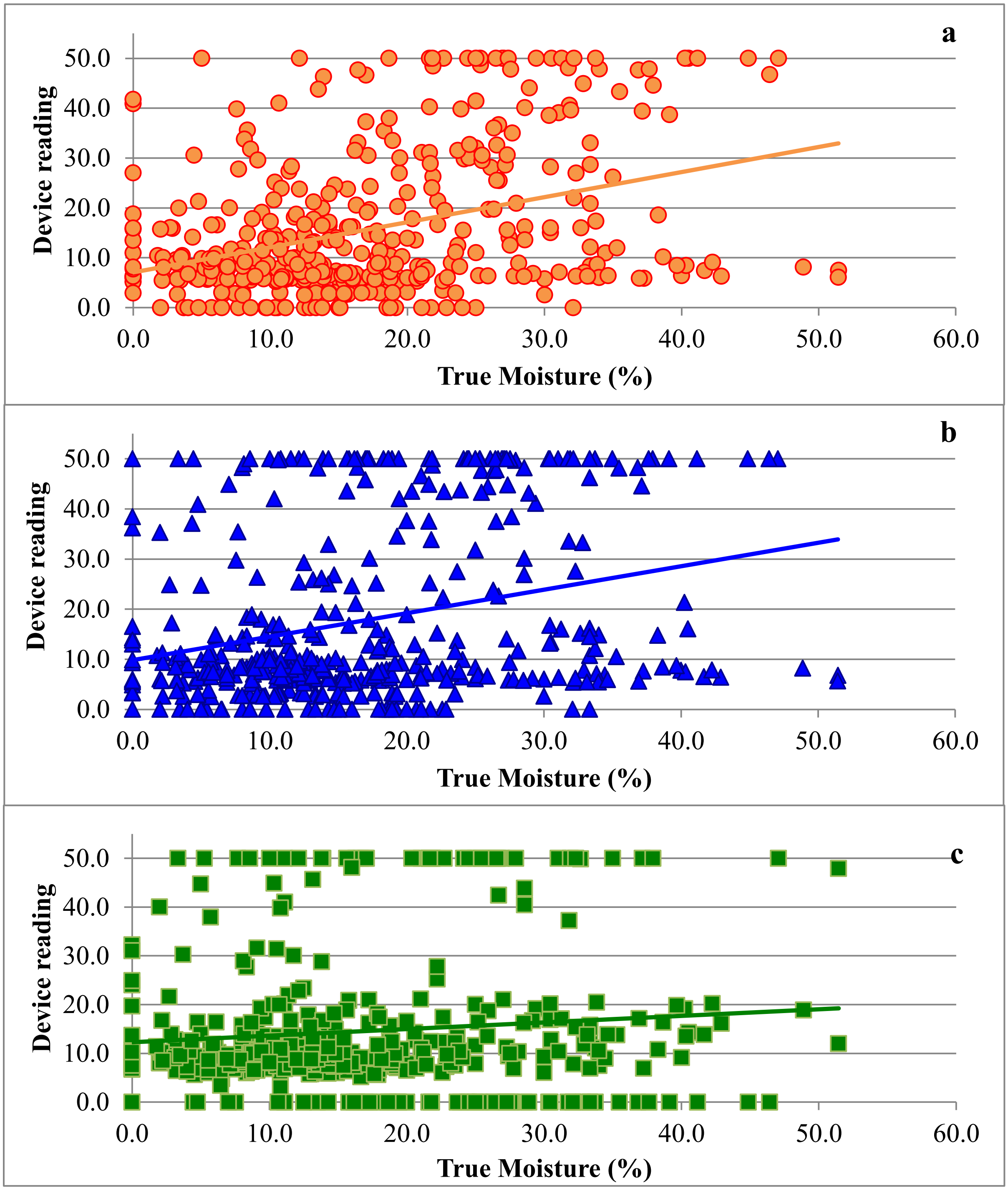
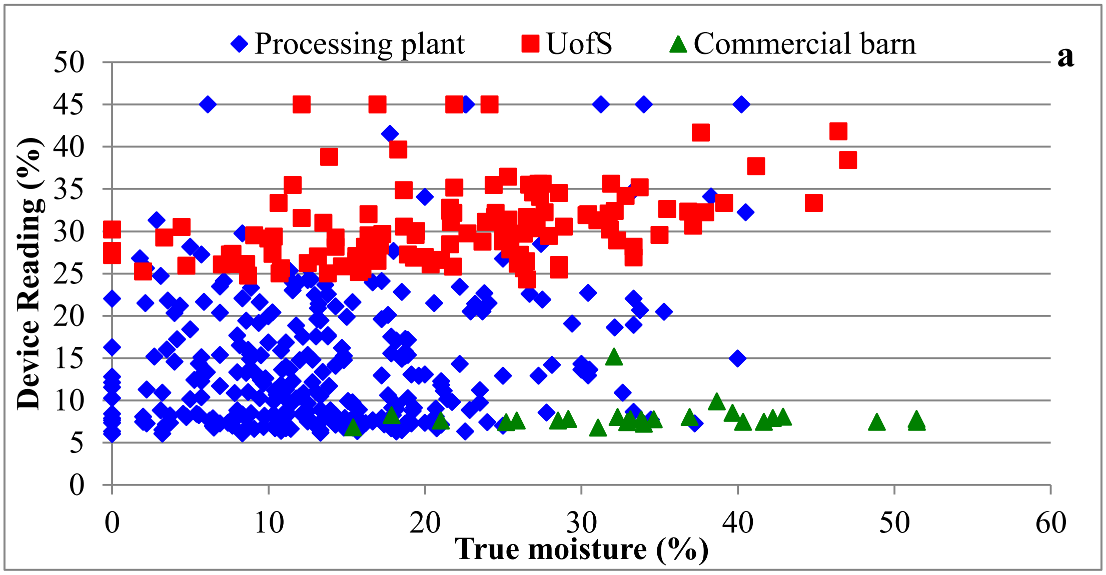


Figure 4.5 Comparison of back (a), wing (b), and breast (c) feather data gathered using Construction 1 during field testing and true moisture determined by gravimetric technique.

4.5.4 Location specific results

Results of field-testing data failed to indicate any separation between the two devices as well as levels of feather moisture. Thus, a secondary analysis was conducted based on the location of testing to investigate the possibility of a pattern (Figure 4.6).



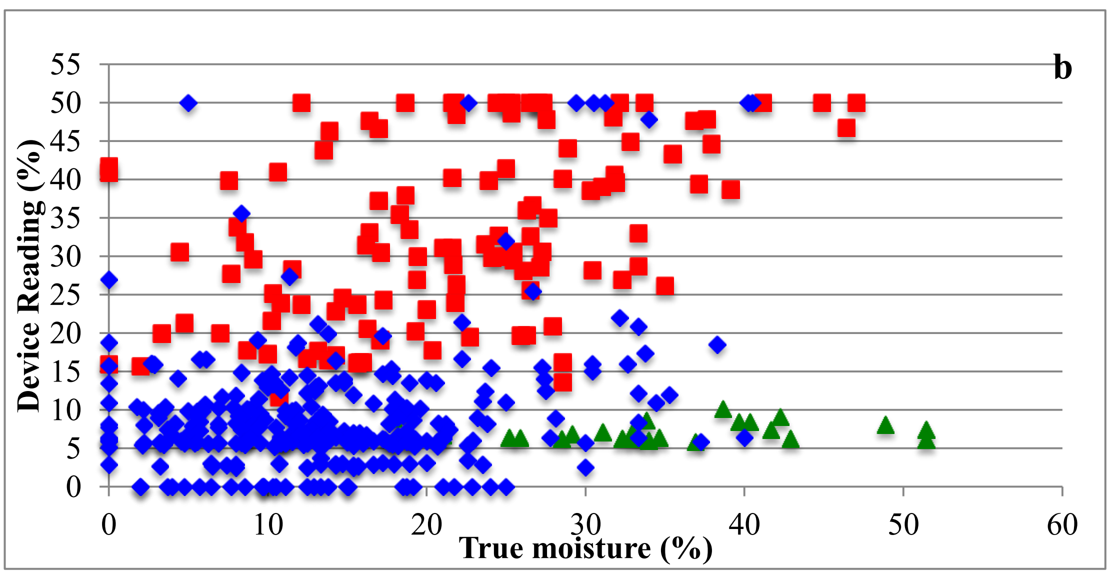


Figure 4.6 Back feather readings from Hay sensor (a) and Construction 1 (b) separated according to the sources of birds.

Figure 4.6 demonstrates a pattern in terms of the source of the tested birds and the moisture content of the feathers. The device reading as well as the range in true moisture of feathers differs depending on the source of birds. A majority of the birds from the processing plant can be categorized as dry or dry with traces of moisture (<30%) based on gravimetric testing of feathers. Readings from both devices using these birds indicate similar patterns where a larger proportion of the readings were below 25%. At the commercial barn, the true moisture of the birds appeared to be in the 'wet' area while the device readings were almost all below 10% (dry). Birds tested at the U of S displayed the most variation in true moisture compared to the previous two sources of birds.

Table 4.5 Results obtained from comparing true moisture content of feathers with the two device readings based on the location (processing plant, commercial barn, U of S) of testing

Device	Testing location	Intercept (c)	b	Adj-R^2	P-value	SE	SSE
Hay sensor	Processing plant	11.45	0.21	0.05	<0.0001	0.47	44.53
	Commercial barn	7.89	0.001	-0.04	0.90	0.32	77.42
	U of S	26.93	0.17	0.13	<0.0001	0.43	59.85
Construction 1	Processing plant	11.37	0.29	0.08	<0.0001	0.52	22.13
	Commercial barn	6.59	0.02	0.02	0.47	0.24	20.30
	U of S	22.11	0.51	0.18	<0.0001	1.08	25.80

Equation used: Predicted moisture = bx +c; b=slope of the device reading, x=device reading

Data collected at the processing plant and the U of S demonstrated a significant relationship between the readings and the true moisture content while commercial barn data did not (Table 4.5). Analyzing data based on location did not improve accuracy of the model created or the sensitivity of the devices.

There were several challenges faced during this research, most importantly, the technique used to determine true moisture of feathers. In phase I - lab testing, determination of true moisture was fairly simple. The feather swatches were washed and dried thoroughly many times. This prevented feathers from containing traces of extra moisture in the shafts prior to data collection, and it was possible to obtain consistent results. Whereas in phase II - field-testing, the shallow shaft of each feather collected was removed to ensure excess moisture was not present. Although care was taken to cut the shallow shafts consistently, it is possible to either have removed too much or too little of it, altering the true moisture content.

Another important factor that may have influenced the true moisture data was the size of the feather sample. The feather samples obtained during field trials were considerably smaller than the feathers used to create swatches. With small samples (<1g), a small change in moisture can have a large impact on true moisture. Moisture could have been transferred from the feathers to the gloves worn during sampling or shaft-removal procedures.

4.6 Conclusions

Returning to the initial objectives of the research, results from laboratory testing suggested that commercially available moisture-sensing devices to be capable of indicating feather moisture. The field results suggest otherwise. If the criteria used for evaluation were individually considered, superiority of one device over the other might be observable. However it is important to assess all criteria and make conclusions accordingly. These devices do not show adequate capabilities in detecting moisture in live birds. Overall, the sensitivity, consistency, and accuracy of the devices appears to be inadequate for the levels of change in moisture.

Conversely, as noted above in the discussion, it is difficult to effectively assess the ability of these devices to measure moisture content, without a proper technique to determine the true moisture content of feathers. The method to determine true moisture content may have resulted in erroneous data, possibly influencing the evaluations of the sensors. As many other moisture-sensing devices are available commercially, it may be worthwhile to test several other devices in future research as well as determine a standard technique to determine true moisture content in a lab setting.

5.0 General Discussion and Recommendations

Transportation of broilers in summer conditions have been researched far more often compared to winter transport conditions of Western Canada. Cold temperatures of the winter cannot be avoided during broiler transportation. Western Canadian winter temperatures are typically in the range of -10°C to -30°C, but it is possible to observe temperatures below -40°C at times. Broilers produce more moisture during transportation in cold conditions than during a normal production cycle in a barn. The moisture produced can often exceed the passive ventilation capacity of the trailer (Watts et al., 2011). Due to limited ventilation in commercial transportation trailers, the environmental conditions vary depending on the location within the load. It is possible for birds in some areas to experience elevated temperatures whereas others will be exposed to reduced temperatures, possibly resulting in hypothermia (Watts et al., 2011). Of all the stressors broilers are exposed to during transportation, Mitchell and Kettlewell (2009) identify thermal stress as the major factor in reducing animal welfare and productivity during transport.

As production and accumulation of moisture during transportation is a likely occurrence, it is crucial to ensure the birds are dry and in excellent health prior to loading. Although barn ventilation is particularly important in winter for removing excess moisture, in order to reduce costs associated with heating, producers tend to lower ventilation in winter, near the end of production cycle (Hermans et al., 2006). As an excessive amount of moisture is accumulated in the barn and the capacity of air to hold moisture reaches the limit, available biological materials including litter and feathers then absorb any additional moisture (Coella, 2003; Hermans et al., 2006; Karl and Trenberth, 2003).

Typically, it is the responsibility of the driver of the transportation vehicle to determine whether a bird is suitable for transportation. While it is possible to identify birds that are visibly sick or injured with less difficulty, it is much more challenging to distinguish birds that are too wet for transportation. The purpose of this research was to see if commercially available moisture-sensing devices from other industries could have the capability to monitor feather moisture. Laboratory testing indicates there is in fact potential to measure feather moisture using tested devices. However, subsequent field-testing results from live birds were less than promising.

Aside from the use of live birds in commercial settings, phase I and phase II followed very similar procedures. Yet, there were significant differences present between the results of the two phases. The devices tested had the capabilities to monitor moisture in various materials including hay, wood, and concrete. As there are no devices currently available to measure moisture content in live animals, this research was unique with limited background information available. Mostly only speculations can be made to explain the difference in results for phase I and II.

The use of live birds and the technique used for determination of true moisture likely play the major factors contributing to the dissimilarity in results. Although the swatches used in phase I were created using live broiler back feathers, they do differ from feathers attached to live birds. For example, feathers used for the swatches were cleaned, washed, and dried several times. It was ensured that there was not any additional moisture present in or on the feathers prior to conditioning them with a pre-determined amount of moisture. The cleaning process likely altered the feathers from their original states.

It is possible to alter the mineral profiles of feathers by washing them (Edwards and Smith, 1984; Furness et al., 1986). Mineral profiles of a dielectric material may alter the electrical conductivity. Electrical properties of minerals are sensitive to changes in chemical impurities and variations (Tyburczy and Fisler, 1995). Assuming that washing alters the mineral profile, potentially, the conductivity of feathers tested in the laboratory and field experiments could be different.

The gravimetric technique used to determine the true moisture content present in feathers was very similar in both phases. In order to prevent moisture present in the shaft section from modifying the true moisture content, the shaft was removed. While caution was taken to remove only the necessary section, it is possible to have removed too much or too little. In addition, there may have been moisture loss or absorption during this process as well. With average sample size being below 1g, a small amount of moisture could have a large effect on the true moisture content. It is difficult to assess the ability of moisture-sensing devices to monitor feather moisture without having absolute true moisture to compare against.

This research only evaluated a handful of commercially available moisture-sensing devices. It is possible that there are far better suited devices for feather-moisture measurement available. Devices evaluated appear to lack sensitivity to differentiate between critical moisture levels. However, considering the number of reputable moisture sensing devices currently available commercially, it is likely that a device capable of measuring feather moisture to exist. Another potential approach in finding a feather moisture-sensing devices would be to utilize available knowledge of existing moisture sensing to develop a specific feather moisture-sensor.

The process of quantifying true moisture of feathers is not as simple as differentiating between wet and dry birds. There are many factors that influence whether a bird should be transported when it is not dry. Distance, health of the bird, ambient temperature, and condition of the transport vehicle are a few. Given that a device is available or created that is capable of determining the moisture content of feathers, the next step would be to define moisture level limits based on factors that play a part in bird welfare during transport.

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