Effects of weather on temperatures of the grain bin components and headspace of a 10-m diameter corrugated steel bin

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ABSTRACT

The mean global temperatures are increasing as a result of climate change. To understand how the change in ambient weather influences the temperature of the stored grain, the temperature fluctuation patterns of the floor, roof, sidewalls, and headspace were monitored from mid-August 2019 to the end of October 2021 in Winnipeg, Canada. The bin was filled with 300 t of wheat at an initial average moisture content of 12.5 ± 0.1% (wet basis). The thermocouples were installed at 17, 9, and 12 locations on the floor, roof (outside), and sidewalls (outside) of the bin, respectively. Sixteen temperature and relative humidity sensors were installed at different locations with varying distances from the surface of the grain in the headspace. The ambient weather (air temperature (°C), relative humidity (%), barometric pressure (kPa), average solar radiation (W/m^2), precipitation (mm), wind speed (m/s), and wind direction (degrees with reference to the north)) were also measured near the bin during the study period.

The temperatures of the roof, sidewalls, and headspace were influenced by the ambient temperature and solar radiation. In Year II (November 2020 – October 2021), the floor, roof, sidewalls, and headspace temperatures were higher by 2.1 ± 0.1°C, 3.9 ± 0.1°C, 3.5 ± 0.2°C, and 1.9 ± 0.1°C than that in Year I (November 2019 - October 2020), respectively. The ambient temperature increased by 1.8°C in year II, compared to year I. These results can be used in the prediction of temperatures in grain bins caused by weather changes.

RÉSUMÉ

Les températures moyennes mondiales augmentent en raison des changements climatiques. Pour comprendre comment le changement des conditions météorologiques ambiantes influence la température du grain entreposé, les modèles de fluctuation de la température du sol, du toit, des parois latérales et de l'espace au-dessus du grain ont été suivis de la mi-août 2019 à la fin d'octobre 2021 à Winnipeg, au Canada. Le silo a été rempli de 300 t de blé à une teneur en humidité moyenne initiale de 12,5 ± 0,1 % (base humide). Les thermocouples ont été installés à 17, 9 et 12 emplacements sur le sol, le toit (extérieur) et les parois latérales (extérieur) du silo, respectivement. Seize capteurs de température et d'humidité relative ont été installés à différents endroits, à des distances variables dans l'espace au-dessus du grain. Les conditions météorologiques ambiantes (température de l'air [°C], humidité relative [%], pression barométrique [kPa], rayonnement solaire moyen [W/m2], précipitations [mm], vitesse du vent [m/s] et direction du vent [degrés par rapport au nord]) ont également été mesurées à proximité du silo pendant l'étude.

Les températures du toit, des parois latérales et de l'espace au-dessus du grain ont été influencées par la température ambiante extérieure et le rayonnement solaire. Au cours de l'année II (novembre 2020 — octobre 2021), les températures du sol, du toit, des parois latérales et de l'espace au-dessus du grain étaient respectivement supérieures de 2,1 ± 0,1 °C, 3,9 ± 0,1 °C, 3,5 ± 0,2 °C et 1,9 ± 0,1 °C à celles de l'année I (novembre 2019 — octobre 2020). La température ambiante a augmenté de 1,8 °C au cours de l'année II, par rapport à l'année I. Ces résultats peuvent être utilisés dans la prédiction des températures dans les silos à grains causées par les changements météorologiques.

KEYWORDS

Grain bin, headspace temperature, roof temperature, floor temperature, climate change, wheat.

MOTS CLÉS

Silos à grains, température de l'espace au-dessus du grain, température du toit, température du sol, changement climatique, blé.

CITATION

Bharathi, V.S.K., F. Jian and D.S. Jayas. 2022. **Effects of weather on temperatures of the grain bin components and headspace of a 10-m diameter corrugated steel bin.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 64: 3.1-3.11. https://doi.org/10.7451/CBE.2022.64.3.1

INTRODUCTION

Change in the weather pattern is one of the frightening effects of climate change (Moses et al. 2015). The Intergovernmental Panel on Climate Change has envisioned a global mean temperature rise of 1.1 to 5.4°C by 2100 (Bale et al. 2002). With the increase in global temperature, the grain stored inside a bin is exposed to warmer temperatures. Interaction between the physical, chemical, and biological factors inside the stored grain ecosystem impacts the quality of the stored grain.

Temperature is one of the most important factors that affect the quality of the grain stored in a bin. The temperature of the grain inside a bin can be affected by various physical and biotic factors (Jian and Jayas 2022). Grain temperatures inside the bin are also influenced by the heat flux from the sidewalls, headspace, and the floor of the bin (Jian et al. 2005). In addition, the temperature of the grain near the floor in contact with a plenum is differently affected, as compared to those with the soil foundation (Jian and Jayas, 2022). The warmer and humid condition deteriorates the quality of the grain stored in the bin (Jayas et al. 1995). An increase in temperature increases the grain respiration rate, enhances the growth and multiplication of other biotic factors present in the stored grain ecosystem such as insects and microorganisms and decreases the germination ability of the grain over time (Nithya et al. 2011).

Moses et al. (2015) have reported that detailed multidisciplinary research is required to understand the effects of climate change on stored grain ecosystem. Understanding the effects of ambient conditions on the temperatures of the components of bins filled with grain is crucial to maintaining the quality of stored grain as temperatures of these components affect grain temperatures. Free-standing, corrugated galvanized steel, cylindrical bin is a common storage structure used in the Canadian Prairies (Alagusundaram et al. 1990). Limay-Rios et al. (2017) surveyed 83 unique storage bins across Southwestern Ontario, Canada, during 2011-2013 and reported that about 98% of the bins were flat bottom, corrugated galvanized steel with conical roof and the median capacity of the bins were 300 metric tonnes. However, the detailed report on the temperatures of the components of the commercial-sized bins influenced by different ambient temperatures in different years is not available. Moreover, reports on the floor temperatures in the presence of a plenum could help develop models using air as the boundary condition rather than the soil.

The aim of the present work was to determine how the weather change influences the temperature fluctuations and gradients at various locations on the floor, roof, sidewalls, and in the headspace of a 10 m diameter bin (flat bottom, corrugated galvanized steel with conical roof) filled with 300 t of wheat, for a period of 26 months. The temperature and moisture profile of the wheat stored in the bin has been reported elsewhere (Bharathi et al. 2023).

MATERIALS AND METHODS

Grain bin

A flat-bottom, cylindrical, corrugated steel bin with 10 m diameter, 5 m high silo cylindrical part, and 3 m high conical roof (from the center of the cone to the cone base), located in the south end of Winnipeg, Manitoba, Canada, was used for this study. At the center of the conical roof, there was a 0.9 m opening (vent), which was used for grain loading. The concrete foundation of the bin was 0.5 m high from the ground. A plenum of 0.35 m depth and a perforated floor were present at the bottom of the bin. A poly tarp with 1 mm opening was placed above the perforated floor before the loading of the wheat. A chute (under the perforated floor) and an auger (above the floor) were installed along the north-west direction for grain unloading. Four ladders and four manholes were installed on the north, south, east, and west sides of the bin. About three hundred tonnes of No.2 Canada Western Red Winter Wheat (AAC Goldrush) with an initial average moisture content of 12.5 ± 0.1% (w.b.) (the moisture content at different locations varied from 11.4% to 13.7%) was loaded into the bin from August 7, 2019, to August 15, 2019, in five batches. The average daily ambient temperature varied from 17.8 to 20.4°C during the loading period (August 7 to 15, 2019). After each loading, the grain surface was leveled manually. The depth of the grain was approximately 4.1 m. Throughout the experimental period, condensation was not observed on the inside surface of the roof or sidewalls.

Weather data collection

A weather station including a temperature and relative humidity probe (CS215, Campbell Scientific, Edmonton), a barometric pressure sensor (CS106, Campbell Scientific, Edmonton), a pyranometer (CS300, Campbell Scientific, Edmonton), a tipping bucket rain gage (TE525M, Campbell Scientific, Edmonton) and a wind monitor (05103, Campbell Scientific, Edmonton) was installed at 10 m from the bin in the south-east direction. The weather data including air temperature (°C) (resolution: ±0.01°C), relative humidity (%) (resolution: ±0.03%), barometric pressure (kPa) (accuracy: ±1.5 hPa), average solar radiation (W/m^2) (sensitivity: ±5 mV/Wm^{-2}), precipitation (mm) (resolution: ±1 tip), wind speed (m/s) (resolution: ±(0.0980 m/s) / (scan rate in seconds), and wind direction (degrees clockwise with reference to the north) (accuracy: ±3°) were measured at 30 min interval from August 1, 2019, to October 6, 2021. The accuracy and resolution of the weather data were based on manufacturer's manual. The daily averages of the collected temperature were compared with those recorded at the Forks, Winnipeg, Canada, by Environment Canada (Environment Canada 2022).

Temperature measurements

Nine vertical cables (OPI^{TM} Systems Inc., Calgary, AB) containing different numbers of sensors were installed, in the headspace of the bin from the ceiling to the floor, for measuring the relative humidity (resolution: ±5%) and temperature (resolution: ±0.1°C) (Fig. 1). The cable at the

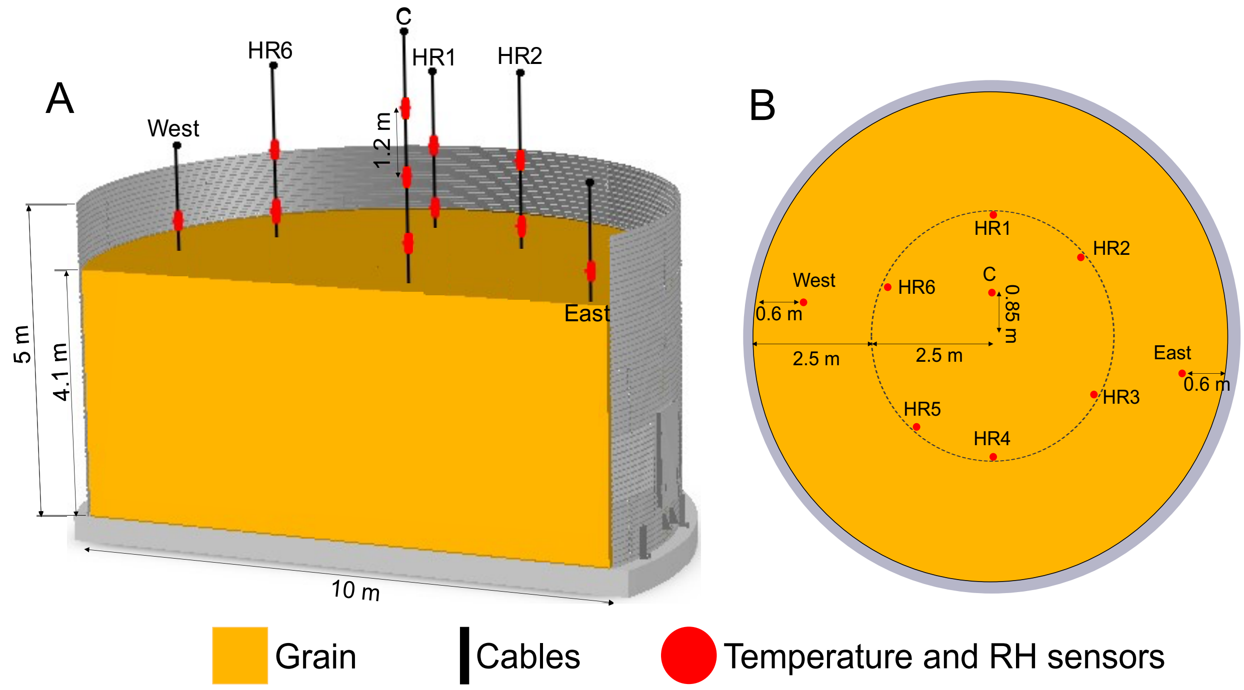

Fig. 1. Cross-sectional view (A) and top view (B) of the cable locations inside a 10 m diameter corrugated steel bin. The sensors at the cables measured temperatures and relative humidities every hour from August 18, 2019, to October 31, 2021. C represents the cable located at 0.85 m from the centre of the bin along the north direction.

center location was 0.85 m from the center of the bin towards North and had 3 sensors at the distance of 0.2, 1.4 and 2.6 m from the surface of the grain to ceiling, and those at 2.25 m away from the bin center (HR1, HR2, HR3, HR4, HR5 and HR6) had sensors at 0.6 and 1.8 m from the surface of the grain in the headspace. The cables that were at 0.6 m from the wall on east and west directions consisted of a sensor each at 0.6 m from the grain surface in the headspace.

A total of 17 thermocouples (precision: ±0.5°C) were installed on the floor, which included eight thermocouples at 0.15 m from the sidewalls along the eight directions (north, south, east, west, north-east, north-west, south-east and south-west), and eight at 2.5 m from the center along all the eight directions, and one was at the center of the floor. A total of nine thermocouples were installed on the outside surface of the roof in such a way that one was installed at 0.6 m from the center of the bin along the north direction, four along each of four directions (north, south, east and west) at 0.15 m from the sidewalls and remaining four at 1.5 m from the sidewalls along the four directions. A total of 12 thermocouples were installed on the outside surface of the sidewalls along four directions (north, south, east, and west) with three thermocouples on each side, at the distance of 0.3, 2 and 4 m from the bottom of the bin. Two thermocouples were installed near the floor on the inside and outside surfaces of the south-east side of the wall, to estimate the temperature difference between inside and outside surface of the sidewall. The sensor on the cable near the east and west side of the wall in headspace and the thermocouple near the south side of the wall on the floor malfunctioned throughout the experimental period.

The precision of the thermocouples was tested in the lab using ice water and boiling water. The resolution of the cables inside the headspace have been provided by the company OPI™ Systems Inc., Calgary, AB. In addition, on comparing the temperatures recorded by the thermocouples and the sensors in the cables were observed to be similar after installation (before loading the grain).

Hourly temperature and relative humidity data from OPI cable sensors and hourly temperature from the thermocouples were recorded from August 18, 2019, to October 31, 2021 (26 months). The data from OPI cable sensors were missing for a total of 22 days and those from thermocouples were missing for a total of 62 days, at all locations during the period of study. The data from November 1 to March 31 and those from April 1 to October 31 were referred to as Cold and Warm Temperature Periods, respectively. Also, November 1, 2019, to October 31, 2020, was considered as year I and November 1, 2020, to October 31, 2021, was considered as year II.

Statistical Analysis

To compare the temperature data recorded at different locations, paired t-test (α = 0.05) was performed using SAS® OnDemand for Academics (SAS Institute Inc., Cary, NC).

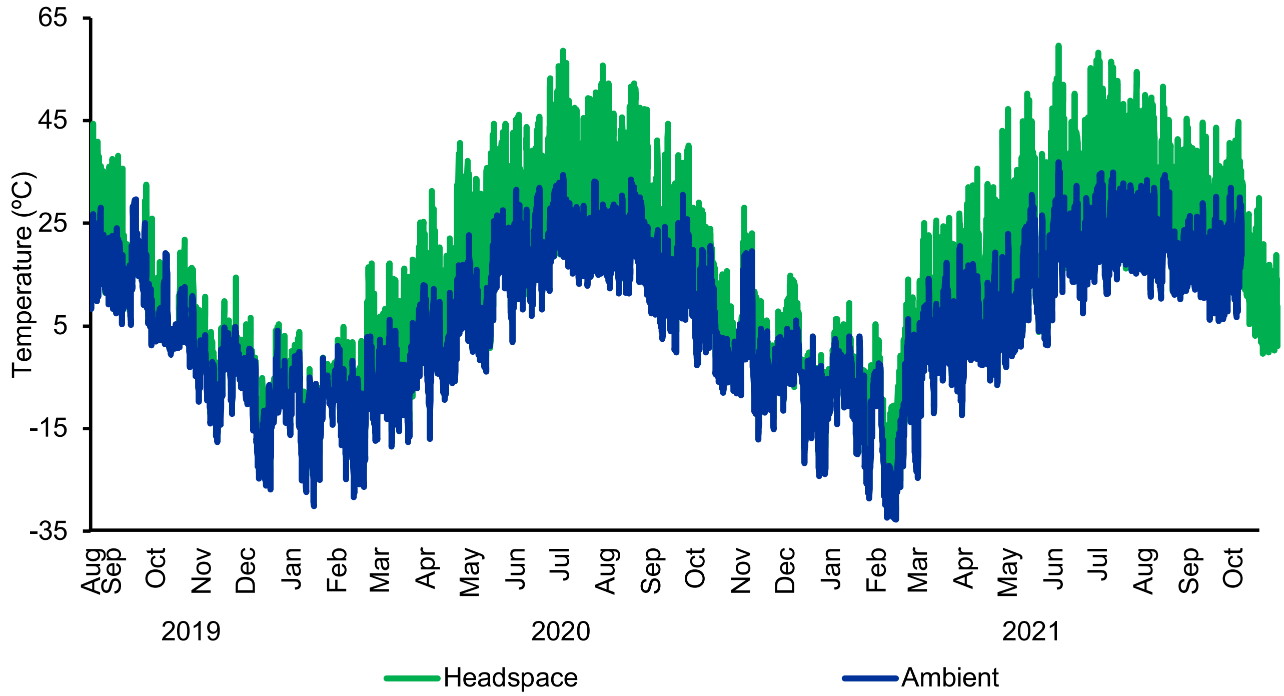

Fig. 2. Headspace temperature inside the bin filled with 300 t of wheat from August 18, 2019, to October 31, 2021. Only the temperatures recorded at the sensor at the distance of 2.6 m from the grain surface on the centre cable are presented.

RESULTS

Weather data

During the 26-month study, the daily average temperatures recorded near the bin were the same ($P = 0.4487$, $t = -0.76$, $N = 755$) (with negligible temperature difference of 0.03 ± 0.03°C) as those recorded at the Forks, Winnipeg. The maximum and minimum temperatures recorded near the bin during year I were 34.4 and -30.7°C, respectively, while those recorded during year II were 36.9 and -33.2°C, respectively. The average hourly ambient temperature recorded during year II was higher by 1.8°C than those recorded during year I. The higher average solar radiation received in year II (160.1 ± 1.8 W/m^2), as compared to year I (148.3 ± 1.7 W/m^2) could have contributed to the increase in ambient temperature in year II. Even though the maximum precipitation recorded in year II (20.9 mm in half-hour) was higher than that in year I (8.1 mm in half-hour), the total precipitation recorded in year II (219.4 mm) was lower than that in year I (233.2 mm). The average ambient relative humidity dropped from 71.9 ± 0.1% in year I to 68.4 ± 0.2% in year II.

Headspace temperatures and relative humidity

The headspace temperatures inside the bin were influenced by the ambient temperature and solar radiation. The temperatures measured at 16 locations in the headspace were hotter than the ambient temperature by 3.7 ± 0.2°C, during the 26-month study period (Table 1, Fig. 2). In the Warm Temperature Period, the headspace temperatures increased or remained the same with increase in height (Table 1). The headspace temperatures were the lowest at HR1 (2.25 m away from the center of the bin towards north) during the Warm Temperature Period. The higher average temperatures at HR4 as compared to those at HR1, during the Cold and Warm Temperature Periods, confirmed the higher solar radiation on the south side, as compared to that at the north side. Similarly, Alagusundaram et al. (1990), who predicted the temperature distribution in grain storage bins using a three-dimensional, finite element, heat transfer model, predicted that the south side of the bin was warmer by about 5 to 15°C than the north side. In the current study, the average temperature differences between HR1 and HR4 were 0.6°C (at both 0.6 m and 1.8 m from the surface), during Warm Temperature Period and 1.2°C (at 0.6 m from the surface) and 0.7°C (at 1.8 m from the surface), during Cold Temperature Period. Montross et al. (2002a) also observed the temperature gradients in headspace because of solar radiation. They reported that the headspace temperature recorded at 0.4 m from the surface was 6°C lower than those recorded at 1.2 m from the surface during periods of higher solar radiation. In the current study, the average difference between the headspace temperature at 0.6 m and 1.8 m at different locations during the day were the maximum of 1.9 and 0.8°C, during Warm and Cold Temperature Periods, respectively.

The average headspace temperature during year II was hotter than year I and the temperature differences observed between years I and II were 1.6 ± 0.1 and 2.1± 0.0°C, during the Cold and Warm Temperature Periods, respectively. This implies that the increase in ambient temperature increased the temperatures in headspace. The maximum headspace

Table 1. Mean, maximum (Max) and minimum (Min) temperatures recorded at different locations in the headspace of a 10 m diameter bin filled with 300 t of wheat, for a period of 26 months.

Location†	Distance from grain surface (m)	Cold temperature periods						Warm temperature periods					
		Nov 2019 to Mar 2020			Nov 2020 to Mar 2021			Apr to Oct 2020			Apr to Oct 2021		
		Mean (°C)	Max (°C)	Min (°C)	Mean (°C)	Max (°C)	Min (°C)	Mean (°C)	Max (°C)	Min (°C)	Mean (°C)	Max (°C)	Min (°C)
Centre	0.2	-4.9 ± 0.1^{a}	17.0	-20.5	-4.8 ± 0.2^{a}	21.4	-31.2	18.5 ± 0.2^{a}	50.4	-10.8	20.0 ± 0.1^{a}	51.8	-5.0
	1.4	-6.4 ± 0.1^{b}	22.9	-25.4	-4.8 ± 0.2^{b}	28.1	-31.4	18.5 ± 0.2^{a}	55.9	-13.8	20.7 ± 0.2^{b}	56.8	-5.7
	2.6	-5.8 ± 0.1^{c}	25.3	-24.8	-4.1 ± 0.2^{c}	25.5	-32.2	19.2 ± 0.2^{b}	58.6	-13.4	21.2 ± 0.2^{c}	59.6	-5.4
HR1	0.6	-6.7 ± 0.1^{a}	20.4	-25.7	-5.2 ± 0.2^{a}	23.3	-32.1	17.9 ± 0.2^{a}	52.7	-13.9	19.9 ± 0.2^{a}	53.4	-5.7
	1.8	-6.4 ± 0.1^{b}	23.6	-25.4	-4.8 ± 0.2^{b}	26.3	-32.1	18.7 ± 0.2^{b}	56.8	-13.8	20.8 ± 0.2^{b}	57.9	-5.7
HR2	0.6	-6.3 ± 0.1^{a}	20.4	-25.2	-4.8 ± 0.2^{a}	23.6	-31.8	18.5 ± 0.2^{a}	52.9	-13.4	20.6 ± 0.2^{a}	53.4	-5.3
	1.8	-6.2 ± 0.1^{b}	22.9	-25.1	-4.6 ± 0.2^{b}	25.9	-31.7	18.7 ± 0.2^{b}	56.1	-13.5	20.8 ± 0.2^{b}	57.4	-5.6
HR3	0.6	-6.4 ± 0.1^{a}	20.4	-24.9	-4.9 ± 0.2^{a}	23.3	-32.0	18.1 ± 0.2^{a}	52.4	-13.4	20.1 ± 0.2^{a}	53.0	-5.5
	1.8	-6.2 ± 0.1^{b}	24.3	-25.2	-4.6 ± 0.2^{b}	26.1	-32.3	18.9 ± 0.2^{b}	56.4	-13.6	21.0 ± 0.2^{b}	58.3	-5.6
HR4	0.6	-5.5 ± 0.1^{a}	21.6	-23.9	-3.9 ± 0.2^{a}	24.8	-30.7	18.5 ± 0.2^{a}	52.8	-12.4	20.6 ± 0.2^{a}	53.1	-4.5
	1.8	-5.8 ± 0.1^{b}	25.8	-25.0	-4.0 ± 0.2^{b}	28.1	-31.8	19.3 ± 0.2^{b}	58.5	-13.2	21.5 ± 0.2^{b}	59.6	-5.2
HR5	0.6	-5.9 ± 0.1^{a}	22.1	-24.8	-4.4 ± 0.2^{a}	25.4	-31.7	18.5 ± 0.2^{a}	53.9	-13.1	20.5 ± 0.2^{a}	54.3	-5.1
	1.8	-5.6 ± 0.1^{b}	25.3	-24.5	-4.0 ± 0.2^{b}	28.2	-31.3	19.1 ± 0.2^{b}	58.4	-13.0	21.2 ± 0.2^{b}	58.8	-5.2
HR6	0.6	-6.0 ± 0.1^{a}	21.4	-24.8	-4.5 ± 0.2^{a}	24.4	-31.4	18.4 ± 0.2^{a}	53.6	-13.2	20.4 ± 0.2^{a}	54.3	-5.2
	1.8	-6.3 ± 0.1^{b}	24.3	-25.3	-4.7 ± 0.2^{b}	26.9	-32.2	18.6 ± 0.2^{b}	57.5	-13.8	20.7 ± 0.2^{b}	58.4	-5.7

† Centre represents the cable located at 0.85 m from the centre of the bin along the North Direction; HR1, HR2, HR3, HR4, HR5 and HR6 represent the cables located at 2.25 m from the centre of the bin (refer to Fig. 1); data from the sensor at the east and west location near the wall are missing because of sensor malfunction.

a, b, c Different lowercase alphabets represent the significantly different mean values recorded using the sensors at varying distance from the grain surface at the cables located inside the bin, using paired t-test ($\alpha = 0.05$)

Table 2. Mean, maximum (Max) and minimum (Min) temperatures recorded at the outside surface of the sidewall at different distances from the bottom of a 10 m diameter bin filled with 300 t of wheat.

Year	Distance from the bottom (m)	North			South			East			West		
		0.3	2	4	0.3	2	4	0.3	2	4	0.3	2	4
Year I†	Mean (°C)	$6.1 \pm 0.1^{a, A}$	$5.8 \pm 0.2^{b, A}$	$6.0 \pm 0.2^{c, A}$	$9.8 \pm 0.2^{a, B}$	$6.9 \pm 0.2^{b, B}$	$8.2 \pm 0.2^{c, B}$	$8.8 \pm 0.2^{a, C}$	$8.0 \pm 0.2^{b, C}$	$6.9 \pm 0.2^{c, C}$	$8.8 \pm 0.2^{a, C}$	$7.5 \pm 0.2^{b, D}$	$7.6 \pm 0.2^{c, D}$
	Max (°C)	42.6	44.3	42.2	55.2	46.1	50.8	51.7	51.0	47.7	57.9	56.6	59.5
	Min (°C)	-25.2	-29.2	-29.6	-23.5	-29.2	-29.0	-23.4	-27.3	-29.0	-22.0	-28.6	-29.2
Year II‡	Mean (°C)	$9.4 \pm 0.1^{a, A}$	$9.4 \pm 0.1^{b, A}$	$9.7 \pm 0.2^{c, A}$	$13.2 \pm 0.2^{a, B}$	$10.7 \pm 0.2^{b, B}$	$11.8 \pm 0.2^{c, B}$	$12.2 \pm 0.2^{a, C}$	$11.6 \pm 0.2^{b, C}$	$10.6 \pm 0.2^{c, C}$	$12.1 \pm 0.2^{a, C}$	$11.1 \pm 0.2^{b, D}$	$11.3 \pm 0.2^{c, D}$
	Max (°C)	42.2	45.0	43.3	55.8	47.4	64.4	51.8	50.6	46.7	55.1	52.9	55.8
	Min (°C)	-22.2	-26.4	-27.3	-22.4	-26.7	-27.1	-20.4	-25.1	-26.9	-21.0	-25.7	-26.8

† Year I represents the period from November 1, 2019 to October 31, 2020; ‡ Year II represents the period from November 1, 2020 to October 31, 2021.

a, b, c Different lowercase alphabets represent the significantly different mean values within the different locations at the same side of the wall, using paired t-test ($\alpha = 0.05$).

A, B, C, D Different uppercase alphabets represent the significantly different mean values within the same locations at different sides of the wall, using paired t-test ($\alpha = 0.05$).

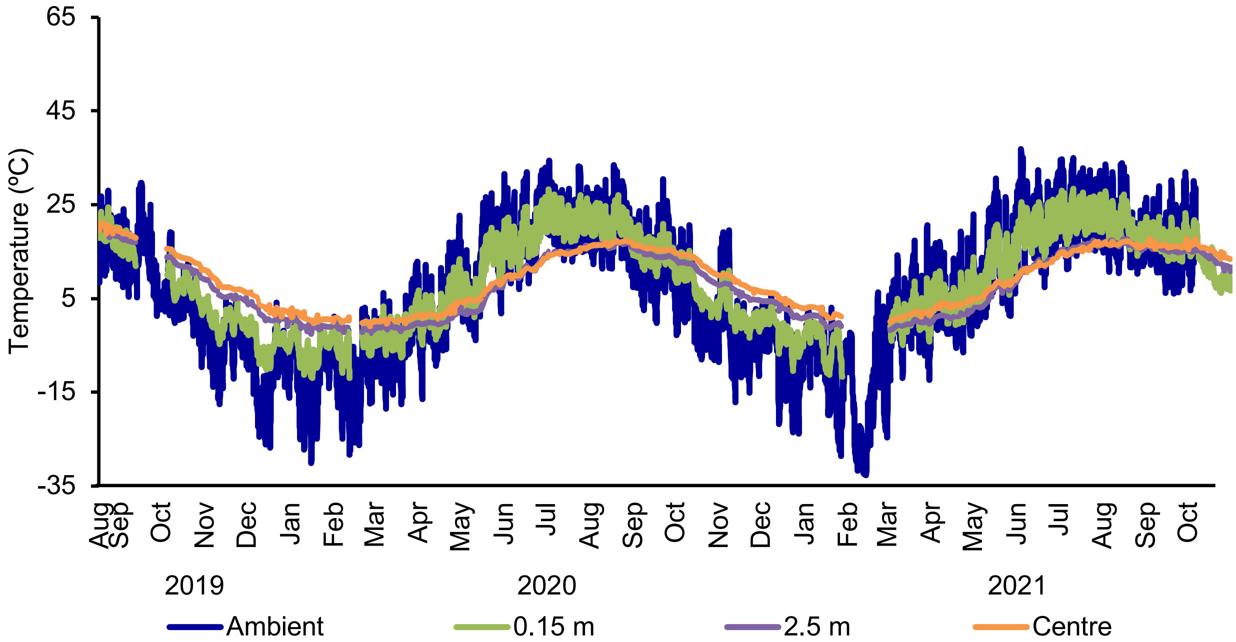

Fig. 3. Floor temperatures at various locations inside the bin filled with 300 t of wheat from August 18, 2019, to October 31, 2021. Only the temperatures along the north direction (0.15 m and 2.5 m from the sidewall) are presented.

temperatures were recorded at 2.6 m (at centre location) and 1.8 m (at HR4 location) from the surface of the grain, and the minimum headspace temperatures were recorded at 0.6 m (at HR1) and 1.8 m (at HR3) from the grain surface, during years I and II, respectively. The hottest headspace temperature recorded in year II (59.6°C), was higher than year I (58.6°C) and the coldest headspace temperature recorded in year II (-32.3°C) was lower than year I (-25.7°C). These data also confirm the influence of the ambient temperature on the temperatures in the headspace inside the bin.

The headspace temperature near the surface of the grain could have been impacted by several factors such as (1) ambient temperature, (2) solar radiation, (3) when the headspace air cools down, it moves towards the bottom of the grain through the intergranular airspace, as a result, the air inside the grain moves into the headspace, (4) when the headspace air heats up due to solar radiation in the day and expands, it moves out of the bin, then the air present in the intergranular space moves into the headspace. The combination of these effects could affect temperature of the headspace near the surface of the grain. Moreover, the temperature difference observed between the grain surface and the headspace could have led to the transfer of heat between the grain surface and the headspace. Thus, the headspace temperature near the surface of the grain could have been influenced by grain temperature, in addition to the ambient temperature and solar radiation.

The average headspace relative humidity during years I and II were 68.8 ± 0.2% and 63.4 ± 0.3%, respectively. During year II, the headspace relative humidity decreased as a result of increase in temperature and decrease in ambient relative humidity. The average headspace relative humidity in the years I and II, during the Warm Temperature Period, were 61.2 ± 0.3% and 56.0 ± 0.3%, respectively; and during the Cold Temperature Period were 79.4 ± 0.2% and 73.8 ± 0.2%, respectively. The headspace relative humidity was higher during the Cold Temperature Periods than the Warm Temperature Periods, due to the change in the headspace temperature. Lawrence and Maier (2011) and Lawrence et al. (2012) also reported variations in the temperature and relative humidity in the headspace of a silo because of change in solar radiation, wind speed and ambient air infiltration.

Floor temperatures

Temperatures on the floor, especially near the wall, inside the bin were mainly influenced by the ambient temperature. The temperatures near the wall followed the trend of ambient temperature (Fig. 3). Temperatures at the center and locations that were 2.5 m away from the center along various directions exhibited temperature lags when compared with those near the sidewalls and the ambient temperature.

The maximum and minimum temperatures recorded during the 26-month experimental period, were 20.0 and -1.0°C at the center of the floor, respectively; were 20.6 and

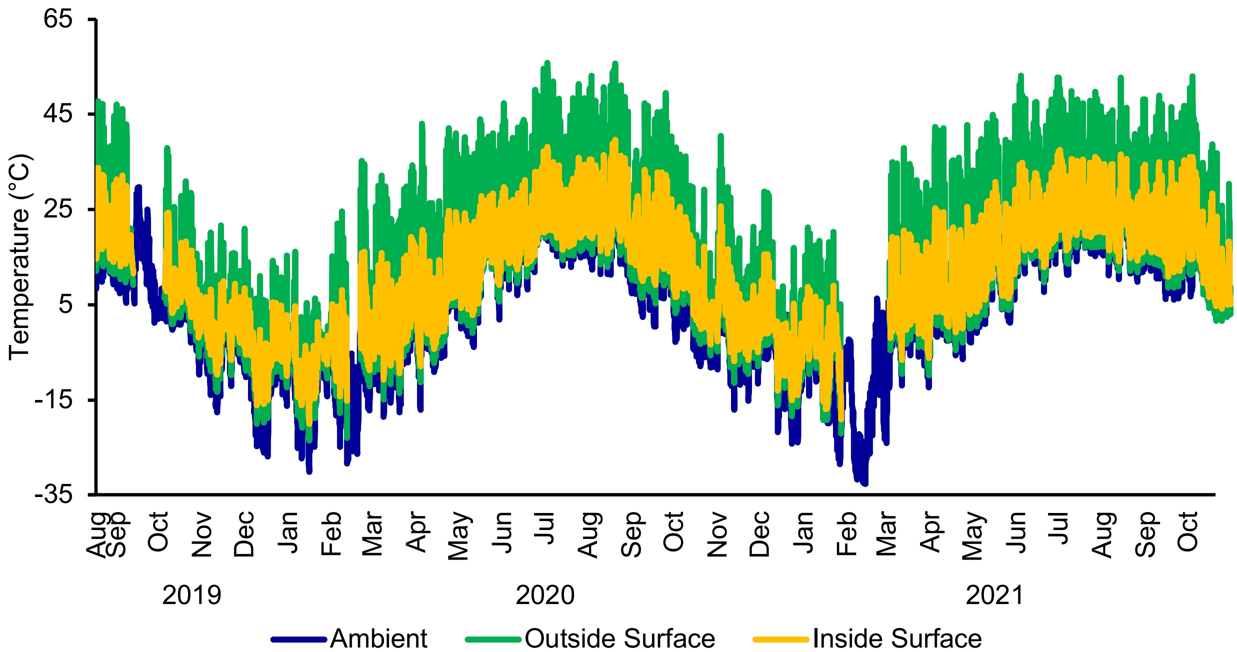

Fig. 4. Temperatures on the roof and sidewall of a 10 m diameter corrugated steel bin filled with 300 t of wheat from August 18, 2019, to October 31, 2021. Only the temperatures along the south direction are presented.

-2.6°C, respectively at 2.5 m from the center; and were 38.4 and -12.0°C, respectively at 0.15 m from the sidewalls. The average absolute temperature gradient between the locations near the wall and their corresponding locations at 2.5 m away from the center was 1.6 ± 0.0°C/m and was 0.4 ± 0.0°C/m between center and 2.5 m away from the center. Among the average temperature differences observed at various locations recorded at 2.5 m from the center, the highest (-2 ± 0.0°C) was observed between north and south direction locations. These results implied that the effect of ambient temperature on the temperature of floor decreased with increase in distance from the sidewalls. Lo et al. (1975) also have predicted that as the distance from the wall increases, the effect of seasonal temperature and moisture change of the wheat stored in a bin decreases.

Among the temperatures recorded at the seven locations near the wall on the floor, the temperatures at the south-east, south-west and east locations were the highest during the Warm and Cold Temperature Periods. Similarly, the temperatures at south, south-east, south-west and east were the highest, during the Warm and Cold Temperature Periods, at 2.5 m from the center of the floor. The floor temperatures along west and north-west direction were lower than those along the east direction. This could be attributed to the presence of the auger from center to outside of the bin in north-west direction. Temperatures along the north direction were the lowest during the Cold Temperature Period, since north side of the bin received lower solar radiation, compared to other locations.

The average temperature differences observed between year I and year II were 1.6 ± 0.0, 1.7 ± 0.0 and 2.6 ± 0.1°C at the center and 2.5 and 0.15 m from the sidewall, respectively. Thus, the increase in ambient temperature in year II, affected the floor temperature near the wall, followed by those at 2.5 m away from the center, and center.

Roof temperatures

The average temperatures on the outside surface of the roof were 2.5 ± 0.4°C higher than those of the ambient air temperatures during the 26-month experimental period (Fig. 4). The temperatures on the roof were mainly affected by the ambient temperature and solar radiation. This could be confirmed from Fig. 5, where the roof temperatures at all the locations were either equal to or higher than the ambient temperature during the Cold and Warm Temperature Periods.

Temperatures along the south and west directions on roof at 0.15 m from the sidewall, were hotter than those along north and east directions during the 26-month experimental period. This was because south and west directions received more solar radiation than the other directions. Similar to the floor, temperatures on the roof were also higher during year II than year I, due to the higher ambient temperature in year II. The average increase in temperature at various measured locations on the outside surface of the roof during year II, was 3.9 ± 0.1°C, compared to year I. The maximum and minimum temperatures recorded on the outside surface of the roof during year I were 71.7 and -30.6°C, respectively; and those

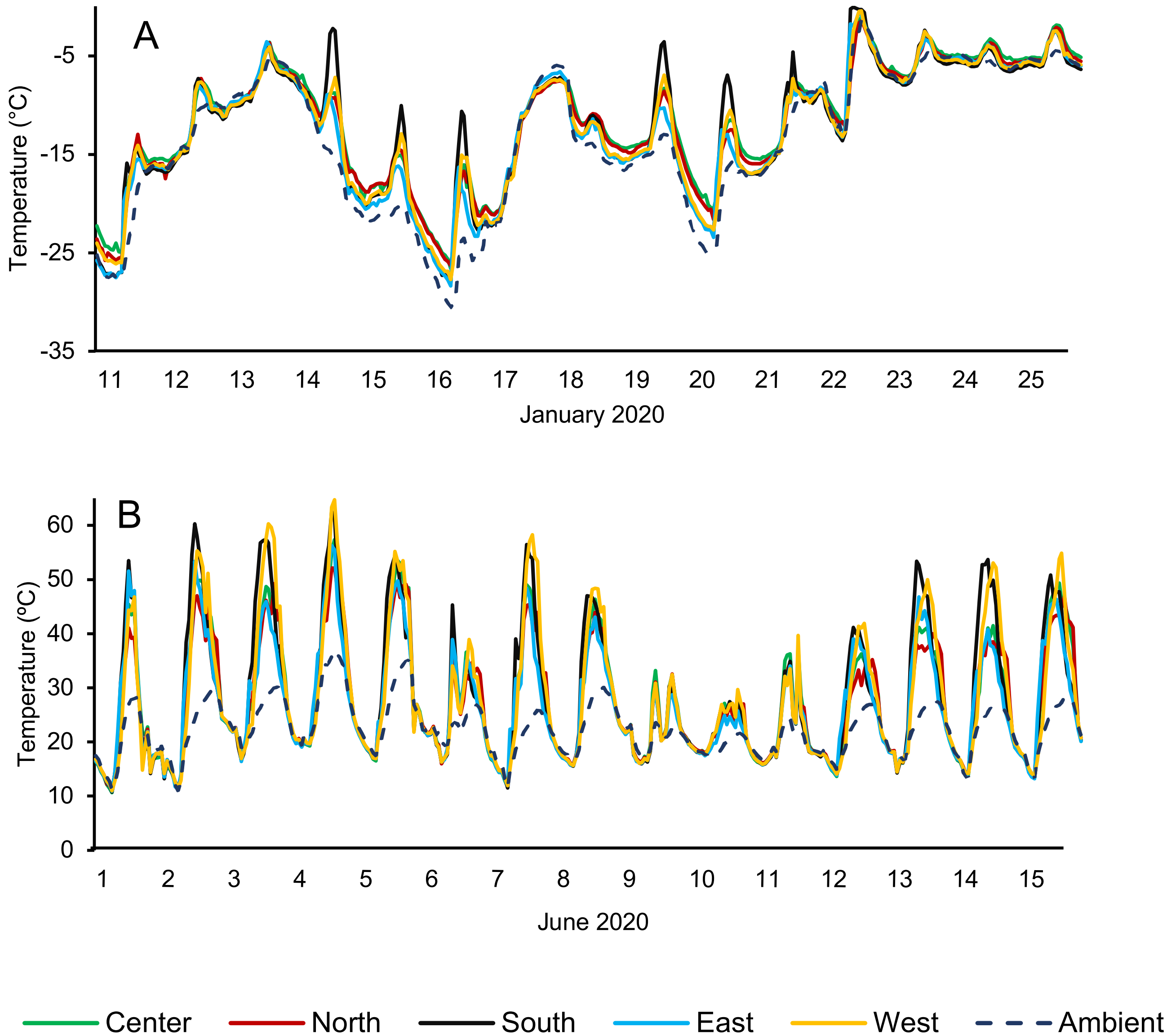

Fig. 5. Roof temperatures at the center and at 0.15 m from the sidewalls along north, south, east, and west directions of a 10 m diameter corrugated steel bin during the Cold Temperature Period (A) and the Warm Temperature Period (B) in 2020. Data for only 15 days are presented.

recorded during year II were 71.8 and -33.2°C, respectively. The minimum temperatures reached on the roof were the same as the ambient temperatures, while the maximum temperatures were hotter than the ambient because of the solar radiation. The higher temperature recorded on the south side of the roof, during the day (Fig. 5a) was mainly because of the higher solar radiation on the south side. Similarly, higher roof temperatures, during the day, especially during Warm Temperature Period (Fig. 5b) could also be attributed to the incidence of solar radiation on the outside surface of the roof. Lawrence and Maier (2011) reported that the headspace air and wall temperature increased during the day because of increased intensity of solar radiation.

Sidewall temperatures

Like the roof, the sidewalls were hotter than the ambient air (Fig. 4) by 2.5 ± 0.3°C from mid-August 2019 to the end of October 2021. Among the temperatures measured at 12 locations on the outside surface of the sidewalls of the bin, the average temperature at 0.3 m from the bottom of the bin on south side of the wall was the highest (11.4 ± 0.1°C), during the 26 months. The north side of the wall recorded the lowest average temperatures, at all the three locations (0.3 m, 2 m, and 4 m). The locations at the south side of the bin wall were hotter than their corresponding locations at the north side of the wall, during the experimental period. At 0.3 m from the bottom of the bin, east and west sides of

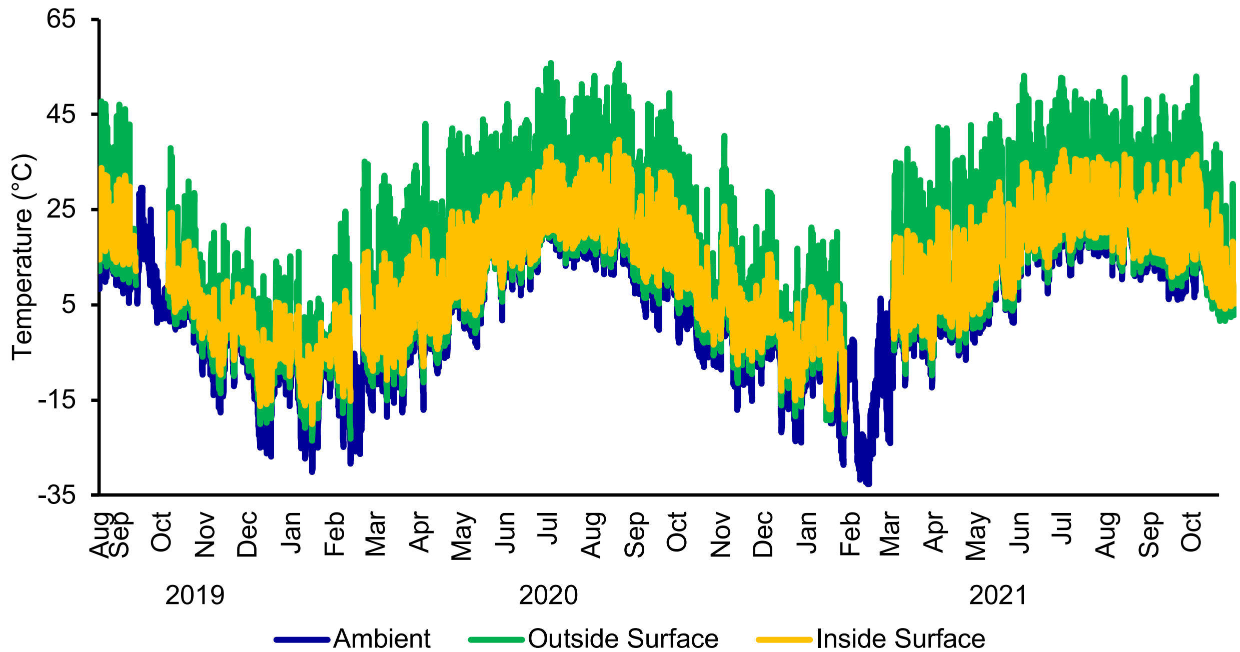

Fig. 6. Temperatures on the outside and inside surface of the south-east side of the wall near the floor of a 10 m diameter corrugated steel bin filled with 300 t of wheat from August 18, 2019, to October 31, 2021.

the wall recorded equal average temperature (Table 2). At 2 m from the bottom of the bin, the temperature at the east side of the wall was hotter than or equal to those at the west side of the wall; while, at 4 m, the temperature at the west side of the wall was hotter. The change in wind direction could have possibly impacted the temperature on the outside surface of the sidewalls.

In general, the temperatures on east and west sides of the wall, increased during forenoon and afternoon, respectively, because of the incidence of solar radiation. The temperatures at 0.3 m from the bottom were hotter than or equal to those at 2 m from the bottom on the wall in all the four directions. The temperatures at 4 m from the bottom were hotter than or equal to those at 2 m, on the wall in all the directions, except east. This was because the temperatures near the bottom of the bin were affected by foundation temperatures and those near the top were affected by the headspace temperatures (Jian et al. 2005).

Like the floor and roof, temperatures on the sidewalls were hotter during year II (average temperature of 10.7 ± 0.5°C) than those during year I (average temperature of 7.3 ± 0.4°C). The maximum and minimum temperatures observed on the outside surface of sidewalls of the bin, during year I, were 59.5 and -30.6°C, respectively; and those recorded during year II were 64.4 and -33.2°C, respectively. These temperatures were lower than those observed on the roof. The temperature on roof were colder during winter and hotter during summer, as compared to those recorded on the sidewalls. The colder surface of roof during winter could be because of the accumulation of snow on the roof; while the hotter surface of roof during summer could be attributed to the higher solar radiation on the surface of the roof, as compared to the sidewalls.

On comparing the temperatures recorded on the outside and inside surface of the south-east side of the wall near the floor (Fig. 6), the outside surface was hotter by 1.3°C than the inside surface, during both years in the Warm Temperature Period, and the inside surface was hotter than the outside surface, by 0.5 and 0.2°C, during year I and II, respectively, in the Cold Temperature Period. The temperature recorded on the thermocouple located at the inside surface of the wall near floor was hotter by 2.3 and 4.6°C, respectively, as compared to the ambient temperature, during the Warm and Cold Temperature Periods. This could be attributed to the presence of grain inside the bin and the effect of solar radiation on the metal surface. These data can be used to validate a mathematical model which involves prediction of the inside surface of the sidewall using the temperatures measured on the outside surface, ambient conditions, and the properties of the wall material.

DISCUSSION

The current study found that the main factor influencing the temperatures on the floor, roof, sidewalls and in the headspace of the bin was the solar radiation, besides ambient temperature. Montross et al. (2002a) reported that the predicted temperatures of the roof, wall and average corn temperature were significantly affected by the absorption of the solar radiation. Montross et al. (2002b) reported the headspace temperature as high as 45°C, inside a 2.74 m diameter corrugated steel bin, in the presence of higher solar radiation; whereas, the headspace temperature was reported to drop to 35°C, during intermittent solar radiation period. The average final predicted corn temperature was found to be about 1.4 to 2.0°C warmer, when the solar radiation and wind speed were included. The grains near the periphery (the wall and the headspace) of the bin was found to be significantly influenced by the solar radiation. Moreover, the heat transfer between the grain surface and headspace air is also influenced by the solar radiation (Montross et al. 2002b). The headspace air temperature near the roof is higher than those near the walls as a result of solar radiation (Lawrence and Maier 2011). These results are in accordance with the findings of the current study.

By including solar radiation as one of the influencing factors, the temperatures of the stored grain can be predicted more accurately. During prediction of moisture movement in a non-aerated grain mass, Montross and Maier (2001) observed the reduction in average corn temperature and moisture accumulation when the solar radiation was neglected, and the impermeable boundary conditions were assumed. Alagusundaram et al. (1990) also included the weather data (solar radiation, wind velocity and ambient air temperature) in the prediction of temperature distribution in stored grain bins. The results of the current study could be used to validate mathematical models which involve the prediction of the temperature of the bin components using the ambient conditions, which in turn could be used to predict the temperature of the grain stored inside the bin using the initial temperature and moisture of the grain. The results of the current study can be used to understand the influence of climate change on the temperature profile of the bin and hence, on the temperature of the stored grain. Warmer temperatures favor the growth and multiplication of insects, mites, and mould. Jian et al. (2018) found that the first two factors influencing the *Cryptolestes ferrugineus* (Stephens) population were the temperature and initial insect numbers. *Cryptolestes ferrugineus* at 25°C can reach its peak density in less than 80 days, while it needs 140 days at 21°C. Tripathi et al. (2021) found a similar trend for the *Tribolium castaneum* (Herbst). Sravanthi et al. (2013) observed visible mould in red lentils stored at 40°C by the end of 3 weeks, whereas at 30°C only after 16 weeks. However, they observed no visible mould throughout the period of storage (16 weeks), at 10 and 20°C. So, the possibility of outbreak of the insects, mites, and mould inside the grain cannot be overlooked and the appropriate measures needs to be taken to prevent/ reduce their outbreak. Considering the effect of increasing global mean temperature on the stored grain and the pest and mould multiplication, further modifications to grain storage structure are required. For example, the temperature of the stored grain can be reduced by adopting appropriate management practices such as aeration and turning. Moreover, with change in global temperature patterns, modifications to meet the safe storage conditions and development of appropriate stored grain management protocols which consider the effect of ambient temperature change are required.

The change in grain quality depends not only on the ambient weather, but also on various other factors such as presence or absence of other biotic factors in the grain bulk such as insects and microorganisms, initial grain temperature and moisture content, accumulation of moisture at a particular location due to leakage of snow/ water into the bin, condensation, or moisture migration due to convection currents. Considering the complexity of the interaction of these factors, it might be misleading to compare the quality of the wheat grain stored inside the bin based on ambient condition only. Hence, the change in grain quality, moisture content and temperature has been reported in detail elsewhere (Bharathi et al. 2023).

CONCLUSIONS

During the study period, the ambient temperature was higher by 1.8°C in year II, than year I. As a result, the average temperatures in year II were higher by 1.9 ± 0.1°C in the headspace, 2.1 ± 0.1°C on the floor, 3.9 ± 0.1°C on the outside surface of the roof and 3.5 ± 0.2°C on the outside surface of the sidewalls, than those in year I. The temperature distribution varied with varying locations on the floor, roof, sidewalls and in the headspace. On the floor, the effect of ambient weather decreased with increase in distance from the sidewalls. The south side of the bin received more solar radiation than north side. The roof was colder in Cold Temperature Period and warmer in Warm Temperature Period, than sidewalls. This study showed that the floor, roof, sidewall, and headspace temperatures of the bin were differently influenced by the solar radiation. During the 26-month period, the temperatures on the floor, roof, sidewalls and in the headspace of the bin were warmer by 2.5 ± 0.3°C, 2.5 ± 0.4°C, 2.5 ± 0.3°C and 3.7 ± 0.2°C than the ambient air temperature, respectively. In addition to the ambient temperature, the temperature of the bin at various locations also depends on the incidence of solar radiation.

ACKNOWLEDGEMENT

This work was supported by the Natural Sciences and Engineering Research Council of Canada [grant number RGPIN-2018-04420 to Jayas] and the University of Manitoba Graduate Fellowship (Bharathi). The authors thank Alireza Salarikia, Md Abdullah Al Mamun, Rahul Tripathi, Vignesh Rajendran and Darsana Divagar for their help in instrumentation and loading of bin; Dale Bourns, Marcel Lehmann and Matthew McDonald for their technical assistance.

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