Scientific Research Publishing

Journal of Sustainable Bioenergy Systems, 2025, 15(3), 139-154
https://www.scirp.org/journal/jsbs
ISSN Online: 2165-4018
ISSN Print: 2165-400X

Drying Rate of Corn Silage and the Influence of Drying Temperature on the Feedstock Quality

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How to cite this paper: Aliahmadi, M., Cao, Y. and Sokhansanj, S. (2025) Drying Rate of Corn Silage and the Influence of Drying Temperature on the Feedstock Quality. *Journal of Sustainable Bioenergy Systems*, **15**, 139-154.
https://doi.org/10.4236/jsbs.2025.153008

Received: March 24, 2025
Accepted: August 31, 2025
Published: September 3, 2025

Abstract

Corn silage is produced from the entire corn plant, which is chopped and stored before the grain reaches full maturity, allowing for fermentation. This type of silage is a highly desirable feed for large animals, particularly dairy cows. In recent years, an industry has developed around the artificial drying of wet corn silage to extend its shelf life and facilitate repackaging and transportation. However, data on the drying rates of corn silage at high temperatures are scarce in the open literature. In this study, commercially grown and ensiled corn silage was fractionated into three nominal particle sizes: 1.6 mm, 3.2 mm, and 6.4 mm, using screen sizes of 1/16″, 1/8″, and 1/4″. The mass and moisture content of each fraction were recorded. Drying trials were conducted on each fraction using an experimental thin-layer dryer with air temperatures ranging from 40˚C to 220˚C. The drying rate plots versus moisture content showed a linear relationship, indicating that a single drying constant could effectively describe the moisture content over time. The drying rates were systematically analysed to develop a unified diffusion coefficient, expressed as an Arrhenius function of both drying temperature and silage particle size. This diffusion equation provides a convenient method for calculating moisture content over time during the high-temperature drying of the three corn silage fractions. A compositional analysis of the silage dried at temperatures ranging from 50°C to 200°C revealed that the total digestible nutrient (TDN) and other constituents varied with drying temperature, but these variations remained within the range of published values.

Keywords

Corn Silage, Fractionated Silage, Drying Rate, Arrhenius Function, Activation Energy, Diffusion Coefficient, Nutritional Quality

1. Introduction

Corn silage is made from chopped corn plants (about 6 mm in size) mixed with corn grain. The harvest occurs before the grain reaches full maturity and dryness. According to Jones M. Coleen *et al.* (2023) [1], corn harvested as silage yields the greatest quantities of energy per hectare. At the time of harvest, the chopped portions of leaves and stalks have a moisture content of 60 to 70% on a wet mass basis (wb). In contrast, the grain has a moisture content of around 40% - 50% wb. On a mass basis, corn grain makes up about 30% of the total plant weight [2]. The kernel contributes significantly to the starch content of the silage. The chopped mix of partially green plants at harvest is warm and moist, making it prone to oxidation and microbial growth. To minimize losses, the chopped mix is placed in a fully or partially confined space (such as a silo pit or bag) and pressed to remove oxygen [3]. In the absence of oxygen, the silage undergoes an anaerobic fermentation process, becoming stable at an acidity of pH 3.5 to 4.5. This fermentation process typically takes 3 to 5 weeks to complete. The biomass is then ready to be used in mixed rations for animal feed.

Corn silage has a high moisture content, typically ranging from 60% to 70% (wet basis). Once removed from the silage pit or bag, it must be used immediately to minimize dry matter loss and prevent oxidative fermentation. Muck (2011) [4] estimates dry matter losses of 1% - 2% during filling, 1% - 4% during fermentation, 0% - 2% due to leaching, 1% - 10% during storage, and 1% - 10% during feeding. The wide range of losses during storage and handling highlights the importance of minimizing these dry matter losses. An international patent [5] describes a process for dehydrating corn silage to reduce dry matter loss. The patent outlines a method for drying silage at temperatures below 55˚C to achieve a moisture content of 15%. In recent research, Hisadomi & Oba (2022) [6] evaluated the nutritional quality of corn silage dehydrated using a commercial rotary drum dryer, where the exit temperature was reported at 90˚C. The slight decrease in nutritional factors was not statistically significant. Additionally, a comprehensive review by Odjo *et al.* (2015) [7] on the effect of corn grain drying on nutritional quality found no consistent impact on feed quality at drying temperatures up to 140˚C.

Corn silage, the fermented product of the entire corn plant, is a common biomass for drying. Its physical properties, moisture content, bulk density, and particle size, significantly influence the drying process. Fresh corn silage typically contains 65% - 70% moisture (wet basis), which must be reduced to about 15% for stable storage [8]. Its hygroscopic nature makes it prone to moisture reabsorption, requiring careful control of the drying environment to preserve product quality. The bulk density varies based on chopping and packing, ranging from 600 - 700 kg/m^3 when compacted [9]. Particle size also plays a critical role; chopped lengths of 1 - 4 cm result in a wide range of aerodynamic behaviors [10], influencing drying rates and necessitating size-based fractionation for efficiency. Thin-layer drying studies have shown that drying rates increase with temperature, although low-temperature drying demands precise airflow and residence time control [11]. Aerodynamic separation can enhance drying by routing lighter, faster-drying particles like leaves out early while retaining denser parts like cobs for extended drying [8]. Additionally, Canadian corn silage hybrids with higher grain content tend to be denser and less fibrous, affecting drying behavior [9]. Importantly, McDonald *et al.* (1991) [12] emphasized achieving a target dry matter range of 30% - 35% to minimize effluent and optimize fermentation, while Wilkinson and Davies (2012) [13] cautioned that overly dry silage can compromise aerobic stability during storage due to poor compaction and increased oxygen exposure. These findings together highlight the importance of balancing drying efficiency with silage stability and quality preservation, while addressing the inherent variability in herbaceous biomass properties that challenge uniform drying [14].

High-temperature drying of corn silage and other types of grains including barley silage have been researched and occasionally practiced in Canada over the past 30 years. At least three agricultural processing concerns in Alberta dry corn silage and repack the material into compressed bales for export. Rotary drum dryers are used for drying silage as well as disinfestation against microbial and insect contamination [8]. The dryers are of a concurrent single-pass drum configuration. Upon entering the dryer, the suspended wet material blends with the hot air and travels the length of the dryer toward the exit. The dried solids separate from the solid particles in the cyclone. The hot solids enter the cooler where the solids are cooled to room temperature before being packed into bales or pellets.

The optimal design and operation of a typical rotary drum dryer depend on how quickly the material dries [15]. The drying speed is influenced by factors such as the drying temperature, the moisture content of the material, and the material's residence time in the dryer [16] [17]. Drying a thin layer of material in the laboratory provides essential data for designing a full-scale dryer. The procedure for setting up the thin-layer equipment and the method for data analysis are well-established in ASABE S448 (2001) [18].

Previous studies on drying agricultural products underscore the importance of understanding the dynamics of moisture diffusivity and activation energy, which contribute to the development of effective drying models and the optimization of the drying process [14]. Particle size and shape control the rate of drying because moisture needs to diffuse through the particle to reach the surface for evaporation [19]. Extracting moisture from cellular bodies is more challenging than from non-cellular structures because moisture needs to cross cell walls. The drying rate slows down as moisture decreases due to the increased resistance to the flow of water or vapor from inside the particles to the surface [20].

Objective

The objective of this research is to determine the drying rate of fractionated corn silage and to develop a universal diffusion equation that accounts for drying temperature and particle size. The biomass is fractionated into three sizes, each of which is exposed to drying temperatures ranging from 40˚C to 220˚C. Experimental drying data are used to estimate the drying parameters. A commercial feed testing lab quantifies the nutritional characteristics of both the undried and dried corn silage.

2. Experimental Setup

Two sets of corn silage samples were collected for physical and nutritional analysis. The first set consisted of corn harvested in 2022, ensiled on-site at Barr-Ag, Inc., a forage and straw processing plant in Olds, Alberta. These samples were sealed in plastic bags, air-shipped to Vancouver, and refrigerated until analysis. The second set, harvested and ensiled in 2023, was sourced from Nutriva Group farms in Abbotsford, British Columbia, and transported to Vancouver by car. The Barr-Ag samples were used for fractionation tests and drying rate experiments, while the Nutriva samples were employed to evaluate the effect of temperature on nutritional composition.

The moisture content of the samples was measured using the ASABE Standard ASAE S358 procedure for forages. This method involved drying a 25 g sample at 103˚C for 24 hours, with the moisture content determined gravimetrically and expressed on a dry matter basis. Bulk density was measured by gently tapping material into a beaker, adding more until it was filled to the brim, and then weighing the contents. Bulk density was calculated as the mass of the material divided by the volume of the beaker [21]. The particle density was measured using a gas pycnometer (Quantachrome Instruments, Boyton Beach, FL, USA; Model MVP-D160-E). For fractionation and mass analysis, a tap sieve shaker equipped with sieves of various sizes was used to separate the material.

The drying rate of corn silage was measured using a thin-layer dryer developed at the biomass processing lab at UBC [22]. A continuous airflow of 50 L/min, sourced from the UBC campus utility line, maintained a temperature of 20˚C ± 5˚C and a relative humidity of 70 ± 5%. This air passed through an in-line electrical pre-heater (Omega, AHP-7561) to control the dryer temperature. Once the desired drying temperature was reached, the biomass samples were spread thinly on a sample holder tray. A digital balance (Sartorius, model: Quintix 412-1S) continuously recorded the mass of the samples, transmitting the data to a computer for recording in an Excel file. Experiments were conducted in duplicate to ensure the reproducibility of the results.

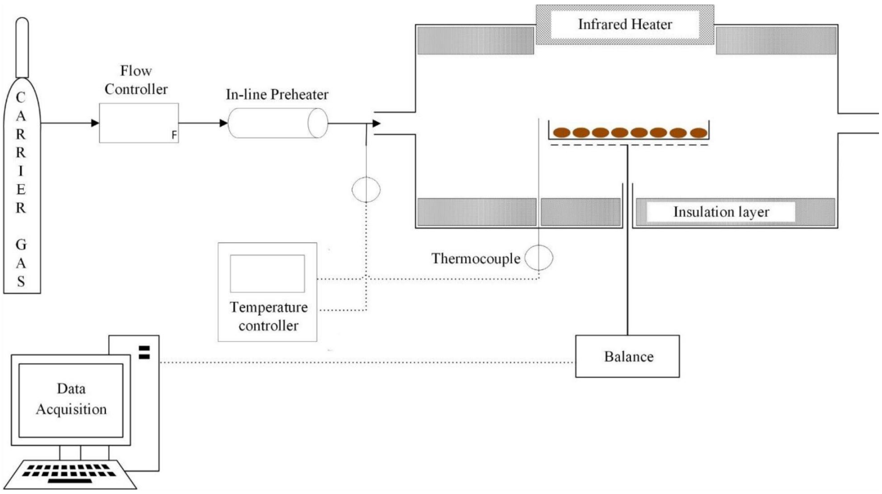

Figure 1. Schematic of the dryer apparatus (components are not to scale).

As shown in **Figure 1**, a lab-scale thin-layer dryer was used to continuously measure the mass of biomass samples during drying tests. The procedure involved conducting thin-layer drying experiments at controlled temperatures of 40, 60, 80, 100, and 200˚C. Once the desired temperature was stabilized, wet biomass samples were loaded into the dryer chamber. A digital balance recorded the mass in real time and transmitted the data to a connected computer. Each experiment was conducted in duplicate to ensure the reproducibility and reliability of the results.

2.1. Kinetic Drying Equations

The moisture ratio (MR) is a dimensionless value that represents the state of moisture within a drying product. It is defined as:

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{Me}}{\mathrm{Mi} - \mathrm{Me}} \tag{1}$$

where M is the moisture at any time (dry basis, db), Me is the equilibrium moisture content (db), Mi is the initial moisture coned (db), MR the moisture ratio (dimensionless).

For a small sample, such as corn silage, the change in moisture can be approximated using the following equation:

$$\mathrm{MR} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D}{4r^2}.t\right) \tag{2}$$

where r is the particle radius (m), D is the diffusivity (m^2/min), t the drying time (min).

To simplify mathematical modeling, several agricultural drying researchers (as summarized by Brooker *et al.*, 1982) [23] suggested setting the scaling coefficient $8/\pi^2$ to 1 leading to [24].

$$\mathrm{MR} = \exp(-kt) \tag{3}$$

where k is the drying constant min^{-1} representing the diffusion term,

$$k = \frac{\pi^2}{4r} D \tag{4}$$

The diffusion coefficient (*D*) is measured in m^2/min plotting ln (MR) versus time (*t*), one can estimate both the drying constant (*k*) and the diffusion coefficient (*D*). The temperature dependence of *D* is commonly described using the Arrhenius equation [25].

$$D = Do \exp\left(-\frac{\mathrm{E}}{\mathrm{R}\, T_{abs}}\right) \tag{5}$$

where *Do* is the Arrhenius factor (m^2/s) ($m^2 \cdot s^{-1}$), E is the activation energy (kJ/mole), R is the perfect gas constant 0.008314 [kJ/(mole.K)], T_{abs} is the absolute drying temperature (K). Additionally, the diffusion coefficient *D* is related to the drying constant *k* and particle size *r* by:

$$D = \frac{4r^2}{\pi^2} k \tag{6}$$

A plot of Ln(*D*) vs. $1/T_{abs}$ will be linear with the intercept being Ln (*Do*) and the slope being E/R. This can be expressed as:

$$\mathrm{Ln}(D) = \ln(Do) + (\mathrm{E/R})(1/T_{abs}) \tag{7}$$

The drying constant *k* was calculated by using the value of *D* and the particle size *r* in Equation (4).

3. Results

3.1. Particle Size and Mass

Table 1 presents the average moisture content, its variations, and the mass fractions for the Barr-Ag samples. The largest mass fraction, 66%, consisted of particles retained on the 4 mm sieve (s > 4 mm). Approximately 23% of the particles were between 1 mm and 4 mm in size (1 mm < s < 4 mm). The mass fraction of particles smaller than 1 mm (s < 1 mm) was about 11%. Corresponding moisture contents decreased from 64.1% (wb) for the large particles to 53.3% (wb) for the smallest ones. The unfractionated biomass blend had an average moisture content of 62.2%. The average moisture content of dried silage Barr-Ag, was 9.4%. Notably, the standard deviations for moisture content were relatively large, especially for the smaller particles. The average bulk density for dry and wet silage was 140 kg/m^3 and 309 kg/m^3, respectively. The average particle density of dry silage, as measured by the pycnometer, was 1166 kg/m^3.

Table 1. Moisture content of the whole and fractionated corn silage.

Particle size (s) ranges (mm)	Moisture content (wb %)			Mass fraction
	Average	Std dev	No. samples	% mass
s > 4 mm	64.1	0.9	6	66
1 mm < s < mm	57.9	3.9	6	23
s < 1 mm	53.3	3.1	6	11

Continued

Whole moist silage	62.2	1.7	8	-
Whole dry silage	9.4	1.7	28	-

3.2. Estimating Moisture Diffusivity in Equation (4)

For the drying tests, corn silage was fractionated into three particle sizes: 1.5875 mm (1/16″), 3.175 mm (1/8″), and 6.35 mm (1/4″) (**Figure 2**). The larger particles retained on the 1/4″ sieve predominantly consisted of chopped stalks. The 1/8″ and 1/16″ sieves collected smaller particles, mainly composed of leaf fragments and broken stalks. The 1/8″ fraction also contained a noticeable amount of whole and fractured corn kernels. The particle sizes of 1.6 mm, 3.2 mm, and 6.4 mm were selected for fractionation based on their relevance to typical size distributions found in chopped corn silage and their aerodynamic behavior during drying. These sizes align with fractions commonly observed in commercial silage processing, where forage harvesters produce a mix of fine particles (leaves and husk), medium particles (sheath and smaller stalk pieces), and coarse particles (stems and cobs). Selecting these thresholds allows for a practical separation of silage into meaningful groups with distinct drying characteristics. Smaller particles like those under 1.6 mm tend to dry faster due to their high surface area-to-volume ratio, while larger ones above 6.4 mm require longer drying times and potentially different airflow conditions. These grid sizes were also chosen to be compatible with standard sieve sets used in agricultural material classification, facilitating comparison with other research and industry data.

Figure 2. Corn silage particles separated by screen sizes of 1.5875 mm (1/16″), 3.175 mm (1/8″), and 6.35 mm (1/4″).

Figures 3 and 4 present samples of the raw data obtained from the thin-layer drying tests. **Figure 3** shows the moisture ratio (MR) versus time for the 1/4″ particles dried at temperatures ranging from 40˚C to 220˚C, demonstrating an exponential decrease in moisture content over time. **Figure 4** illustrates the moisture ratio versus time for all three particle size fractions dried at 80˚C. As anticipated, smaller particle sizes required shorter drying times. However, the 1/8″ fraction exhibited the slowest moisture reduction, likely due to the presence of whole or fractured maiz-kernels in the sample.

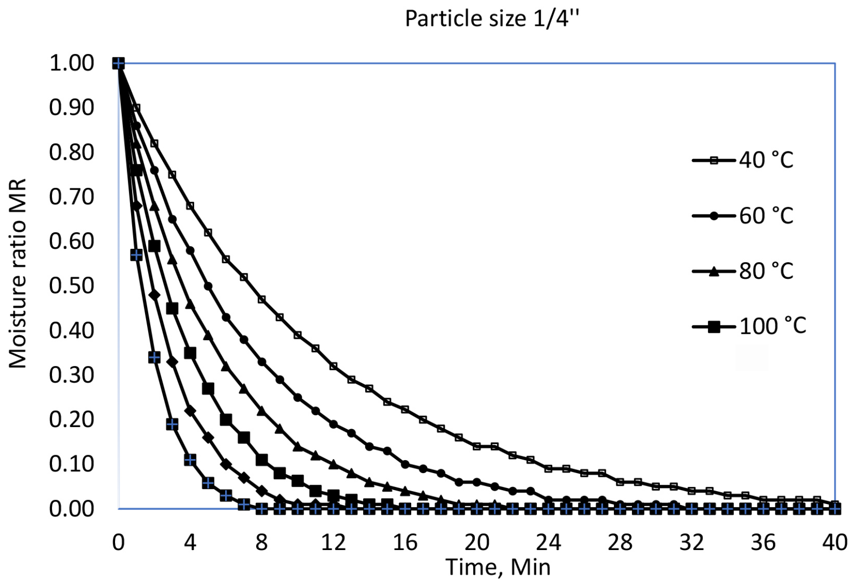

Figure 3. Plot of moisture ratio versus drying time for six temperatures ranging from 40˚C to 220˚C. As the drying temperature increases, the drying time decreases, demonstrating an exponential reduction in moisture content over time.

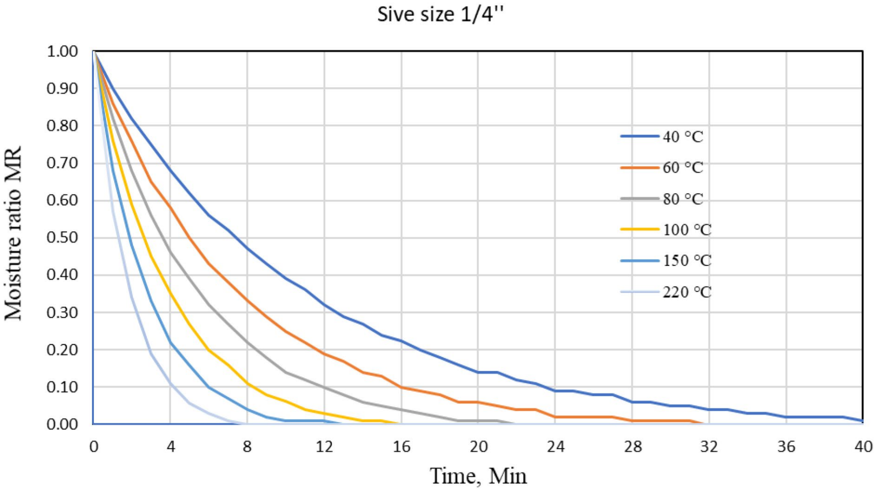

Figure 4. The plot of moisture ratio vs. drying time for the three sieve sizes of 1/4″, 1/8″, and 1/16″ dried at 80˚C. Note, drying rate of 1/8″ particles are slower than the drying rate of ¼″ particles, due to the presence of broken and or whole kernels in the 1/8″ sample.

Figure 5 illustrates the drying rate (dM/dt) as a function of the instantaneous moisture content for 1/4″ particles dried at 80˚C. Similar linear plots were generated for 1/16″ and 1/8″ particles. The drying rate vs. moisture content exhibits a linear relationship with a constant slope across all particle sizes. This indicates that a single drying rate constant is sufficient to represent the drying kinetics of the corn silage analysed in this study.

The drying rate constant k in Equation (3) was estimated using experimental data of M vs. t for each drying temperature and particle size fraction. **Table 2** lists the estimated *k* values in units of min^{-1}. As expected, the *k* values increased with rising drying temperatures. It was anticipated that the drying constant for 3.175 mm (1/8″) particles would be larger than the value of *k* for 1/16″ particles and smaller than the values for ¼″ particles across the entire temperature range. However, this trend was not observed, except at drying temperatures above 100˚C. Further tests are required to quantify the fraction of corn grain in the silage mix.

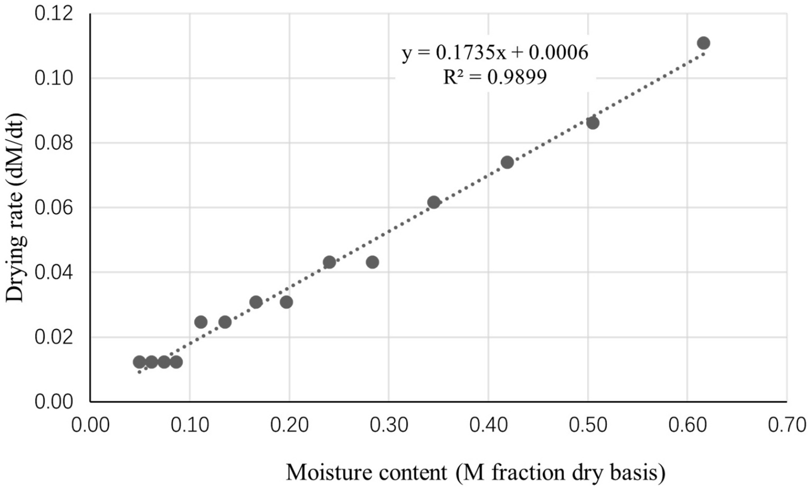

Figure 5. Plot of drying rate dM/dt vs moisture content (M, dry basis) for 1/4″ particles dried at 80˚C.

Table 2. Values of drying constant *k* (min^{-1}) for three sizes of silage dried at 40˚C - 220˚C

Temp (˚C)	1.5875 mm (1/16″)	3.175 mm (1/8″)	6.35 mm (1/4″)
40	0.120	0.097	0.097
60	0.166	0.119	0.144
80	0.231	0.160	0.199
100	0.342	0.276	0.289
150	0.573	0.477	0.439
220	1.083	0.712	0.599

Figure 6 presents a plot of Ln (*D*) vs. $1/T_{abs}$ as derived from Equation (6). The linearity of the relationship is confirmed by the straight line fitting the data and the high R^2 values. The trendlines for Ln(*D*) vs. $1/T_{abs}$ data are nearly parallel, similar to the plots obtained by Kumar *et al.* (2022) [26] for drying foam-covered Mango. The slope of the linear line yields values for E/R, (Equation (7)) while the intercept, where the line crosses the vertical axis, gives the value for Ln (*Do*).

To determine the activation energy E, the slope E/R is multiplied by the perfect gas constant R = 0.008314 kJ/(mole.K). The calculated E values are 13.11, 15.2, and 15.8 kJ/mole with an average of E = 14.7 kJ/mole. The Arrhenius factor *Do* is the antilog (*Do*). The average intercept value from **Figure 6** is 4.83 yielding the constant value for $Do = 2.106 \times 10^{-6}$ m^2/s (please note change in the units). When comparing the calculated *k* using the average Do for mid-size and larger particles from **Table 2** with those from Equation (4) there was a discrepancy. To minimize the absolute differences between the *k* values from **Table 2** and the calculated *k* values from Equation (4), the GOALSEEK function in Excel was used to vary *Do*. The GOALSEEK function minimized the sum of the absolute differences of 12.5% with $Do = 7.62 \times 10^{-6}$ (m^2/s). The final form of Equation (5) becomes:

$$D = 7.62 \times 10^{-6} \exp\left(-\frac{14.7}{0.008314 \times T_{abs}}\right) \tag{8}$$

where *D* is the diffusion coefficient (m^2/s), and T_{abs} is the absolute drying temp in K (Kelvin)

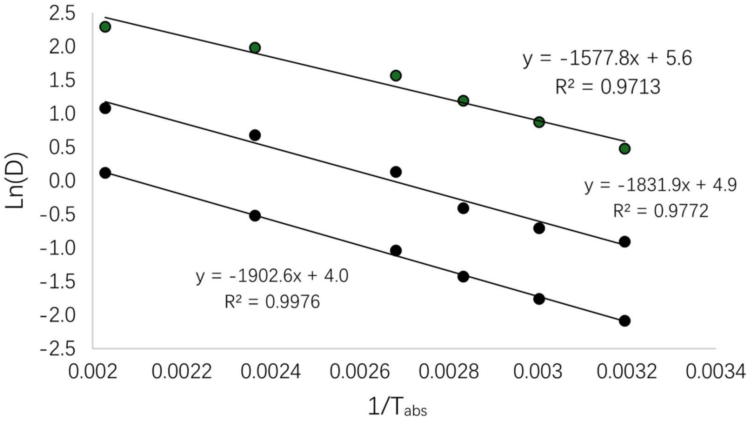

Figure 6. The plot of Ln(*D*) vs. 1/(T_{abs}) for the three sizes of particles.

A key next step in our research was to validate the Arrhenius-based diffusion model beyond controlled laboratory conditions. To this end, we conducted field testing at Barr-Ag Inc., a commercial silage processing facility in Olds, Alberta, where corn silage is routinely dried using a full-scale rotary drum dryer. During site visits, we measured drying air inlet and outlet temperatures, monitored moisture content before and after drying, and compared these operational data points with the predictions generated by our lab-scale Arrhenius model. The observed temperature profiles and moisture reduction trends were in close agreement with the model's forecasts, providing strong initial confirmation of its applicability under real-world conditions. While these results are promising, we acknowledge the importance of further validation using independent datasets—ideally from different harvest years, geographic locations, or dryer designs—to test the model's robustness and generalizability. Such continued efforts will ensure the model is not overfitted to a specific set of conditions but instead offers a versatile tool for predicting drying behavior across a wide range of scenarios. Ultimately, this level of validation will strengthen the model's utility in industrial dryer design and operation, enabling engineers and practitioners to reliably estimate drying performance and optimize processing conditions for corn silage at commercial scale.

4. Drying Temperature and Feed Quality

Several batches of corn silage were collected from Nutriva Group silage bunkers in Abbotsford, British Columbia, and submitted to Cumberland Valley Analytical Services, a feed testing laboratory in Waynesboro, PA. The lab conducted a standard, calibrated Near-Infrared Spectroscopy (NIR) test to determine the key parameters that establish the feeding quality of the biomass [27]. **Table 3** provides a brief description of each compound measured by NIR.

The Total Digestible Nutrient (TDN) content is the most critical aspect of corn silage, representing the digestible portion of the feed, including the sum of digestible fibre, protein, lipid, and carbohydrate compounds. A higher TDN percentage is desirable, as it indicates better feed quality. Similarly, an increase in Non-structural Carbohydrates (NFC), which include starch, sugar, and pectin, is also favourable since these compounds primarily serve as energy sources.

In contrast, an increase in fibre content, indicated by higher Acid Detergent Fibre (ADF) and Neutral Detergent Fibre (NDF) levels, suggests a decrease in the feed's energy content. The starch content mainly reflects the amount of corn grain present in the feed.

Table 3. Description of NIR-measured compounds in animal feedstuff (%). Moisture content (MC) and Dry matter (DM) are expressed as percentages of the entire sample. All other compounds are presented as a percentage of the dry matter (DM) content.

MC	Moisture content, wet mass basis of the entire sample,
DM	Dry matter wet basis of the entire sample
TDN	The digestible portion of a feed, the sum of the digestible fibre, protein, lipid, and carbohydrate components. A larger fraction is desired
ADF	Cellulose, lignin and silica, the least digestible parts of the plant. A higher ADF indicates a lesser digestible feed
NDF	Cellulose, hemicellulose, lignin and silica portions, structural components. Low NDF means more energy available to animal
Starch	Corn silage starch comes from the corn kernels in the feed. Starch plays a critical role in meeting the energy requirements of the livestock.
Ash	Ash content contain essential minerals but excessive ash contains soil that is mainly from silicates. The average ash content of corn silage is 5%. More than 7% may be an indication of soil contamination.
pH	pH 3.5 - 4.5 is optimum, whereas silage pH above and below may reduce intake.
NFC	Non-structural carbohydrates: starch, sugar and pectin content. Higher increases milk yield
CP	Crude protein represents the total nitrogen multiplied by 6.25 to obtain a value for protein content of silage, ranging from 7 to 9%. A higher CP is preferred.

Table 4 presents the numerical values of silage analysis conducted before and after ensiling, with the final column showing the published ranges for the feeding values of corn silage. The variations observed in the nutritional compounds underscore the influence of agronomic practices, climate, geography, and harvest timing on silage quality, aligning with findings from previous research [28] [29]. Additionally, the differences in drying temperatures (50˚C, 100˚C, 150˚C, and 200˚C) likely contributed to the observed variations in the measured values. De-

spite these differences, the nutritional values measured in this study remain within the published data ranges.

Table 4. Measured feed constituents of corn silage before and after fermentation at drying temperatures of 50˚C to 200˚C. Compound fractions are expressed as a percentage (%) of the dry matter.

Feed const.	Field chops prior to ensiling	Maze silage	Dried @ 50˚C	Dried @ 100˚C	Dried @ 150˚C	Dried @ 200˚C	Published [1,2,3] range
MC	69.3	66.2	7.6	5.5	8.0	11.5	65-70
DM	30.7	33.8	92.4	94.5	92.0	88.5	30-40
TDN	66.5	69.6	72.7	68.6	67.7	69.1	62-74
ADF	25.4	24.3	21.9	27.1	25.4	23.5	18-26
NDF	43.9	39.3	35.9	44.7	43.2	41.6	36-48
Starch	26.1	30.9	35.4	26.6	26.0	27.1	25-40
Ash	6.56	5.6	4.8	4.7	6.3	5.9	4.0-5.0
pH	3.3	3.9	3.9	3.7	3.82	3.9	3.5-4.5
NFC	38.9	45.6	50.7	43.0	42.0	43.5	30-40
CP	9.4	7.5	6.8	6.0	6.8	7.1	6.5-10.0

[1]BAYER, 2024 [30], [2]Mullenix and Dillard 2019 [27], [3]Hoffman and Patrick, 2005 [31]

A drop in crude protein (CP) levels after fermentation as listed in **Table 4** is noteworthy and could be attributed to protein denaturation during high-temperature drying, as suggested by Hisadomi and Oba (2022) [6]. This finding underscores the importance of understanding the effects of drying methods on nutritional content when analysing silage samples. In summary, while the data in **Table 4** provide valuable insights into the nutritional composition of corn silage, further research is needed to fully understand the impact of drying processes on its nutritional value. Additionally, considering factors such as drying temperature is crucial for accurate interpretation and comparison of nutritional data across samples.

5. Discussion

The present study sheds light on the kinetics of high-temperature drying of corn silage, particularly in the context of commercial farming practices. The authors note that, to their knowledge, high-temperature drying of corn silage is not currently utilized widely on farms in Canada, and they did not find any publications discussing this practice. The experiments conducted in this research indicate a significant increase in drying rate with higher temperatures, leading to a proportional decrease in drying time. For instance, **Table 5** shows the drying time decreased from 20 - 23 minutes at 40˚C to 2 - 4 minutes at 220˚C. Notably, abnormal drying behaviour was observed for 1/8″ particles compared to drying curves for 1/16″ and ¼″ particles. Furthermore, the study found that the drying rate exhibited a continuous decline with decreasing moisture content, indicating the absence of a constant rate period during drying. This behaviour aligns with previous observations on agricultural products, where diffusion coefficient estimated from drying temperature and particle size.

Table 5. Drying times (minutes) from 61% initial moisture content silage dried to 10% moisture content for the three particle sizes.

Sieve size (mm)	Drying temperature ˚C					
	40	60	80	100	150	220
	Drying time (minutes)					
1/16″	20	14	11	7	4	2
1/8″	23	19	14	8	5	3
1/4″	23	16	12	8	6	4

It is reasonable to assume that the largest fraction of particles would control the drying rate of a blend of silage. In the case of corn silage, the fraction of large ¼″ particles constitutes 66% of the blended mass. Table 2 demonstrates that the drying rate, k, is highly linear with drying temperature for ¼″ particles. The following simple linear equation accurately fits the data:

$$MR = 0.0029T - 0.0172,\ R^2 = 0.99 \tag{9}$$

where T is the drying temperature in ˚C. For practical design purposes, Equation (9) will be sufficient to predict the drying rate of corn silage as a function of drying temperature.

Based on the observations, a practical drying-air temperature range of 80˚C - 120 ˚C is recommended to balance drying efficiency and silage quality. This range significantly reduces drying time while minimizing the risk of nutrient degradation. Although higher temperatures can further speed up drying, they may lead to protein loss and reduced feed value. Conversely, lower temperatures are gentler but inefficient and may risk spoilage. Nutritional analyses showed no major quality loss within the 50˚C - 200˚C range, suggesting that moderate drying temperatures effectively preserve feed quality. Therefore, setting dryers in the 80˚C - 120 ˚C range offers a reliable guideline for efficient and safe silage processing.

6. Conclusions

The particle size distribution analysis shows that approximately 65% of the corn silage particles exceed 4 mm in size. The mid-size range (1 - 4 mm) accounts for about 25%, while the smallest fraction (less than 1 mm) comprises the remaining 10%.

The drying process of the silage primarily occurs during the falling rate period, consistent with the widely recognized exponential drying equation that accurately describes the drying rate kinetics.

The drying rate constant exhibits a clear linear dependence on temperature for the larger ¼-inch particles. To account for the effects of both temperature and particle size, the drying constant is expressed in terms of the diffusion coefficient, taking into consideration variations in particle size.

No clear trend in feedstock properties as a function of drying temperatures between 50˚C - 200˚C was observed, with the variations remaining within the range of nutritional data typically reported for corn silage.

Acknowledgement

The authors gratefully acknowledge the financial support from Agriculture & Agri-Food Canada's Agri-Science Partnership Program, managed by BioFuel Net Canada under the Biomass Cluster Canada initiative (ASC-16-Activity 13). The authors also extend their thanks to Barr-Ag Inc. of Olds, Alberta, and Nutriva Group of Abbotsford, BC, for providing the corn silage samples.

The fee version of Google's AI ChatGPT is used to improve the grammar and readability of the text.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

D	Diffusivity (m^2/s)
Do	Arrhenius factor
MR	Moisture ratio (dimensionless)
M	Moisture content, decimal dry basis
Mi	Initial moisture content (dry basis)
Me	Equilibrium moisture content (dry basis
r	Radius (m)
s	Size