**A Mass Transfer Model of Ethanol Emission from Thin Layers of Corn Silage**

H. M. El-Mashad, R. Zhang, T. Rumsey, S. Hafner, F. Montes, C. Alan Rotz, V. Arteaga, Y. Zhao, F. M. Mitloehner

**ABSTRACT.** A mass transfer model was developed and validated to predict ethanol emission from thin layers of corn silage. The model was developed using experimental data collected from silage placed in a wind tunnel under different temperatures and air velocities. Data from the wind tunnel experiments were used to derive a multiple regression equation that related the overall mass transfer coefficient of ethanol to temperature and air velocity. Evaluation of the model was done using data collected from experiments conducted in a controlled environmental chamber. Ethanol emission was determined from the ventilation rate of the environmental chamber and ethanol concentration in the chamber exhaust over a 24 h period, measured using a photoacoustic gas analyzer. Ethanol concentration in the silage was also monitored throughout the duration of each experiment. Predicted ethanol emission rates were strongly correlated ($R^2 = 0.94$) with values measured in the environmental chamber. A high correlation ($R^2 = 0.96$) was also found between predicted and measured ethanol concentrations in the silage. The model was used to estimate ethanol emission rates from thin layers of lightly packed silage on a dairy farm in California. Model predictions indicate that most of the ethanol contained in the silage could be emitted in the first 10 h after exposing the silage to ambient air temperature ($18^\circ$C to $35^\circ$C) and air velocity (0.1 to 2.0 m s$^{-1}$).

**Keywords.** Corn silage, Dairy farms, Ethanol emissions, Mass transfer coefficient, Modeling, VOC emissions.

Dairy farms are a significant source of volatile organic compound (VOC) emissions. Feed, manure, and cattle themselves are the specific emission sources. Many VOCs have been identified as air pollutants emitted from dairy farms, including alcohols, organic acids, aldehydes, ketones, and esters (Filipy et al., 2006; Shaw et al., 2007; Sun et al., 2008; Ngwabie et al., 2008), with silage being a major source (Alanis et al., 2008; Montes et al., 2009; Howard et al., 2010). The major public health concerns with VOCs are odor and the contribution of these compounds to the formation of ground-level ozone (NRC, 2008).

Ethanol is produced in silage as a result of fermentation. Ethanol concentrations in silage vary with the characteristics of the raw material and the conditions under which the fermentation occurs (Pahlow et al., 2003). Sheperd and Kung (1996) reported that ethanol concentrations in corn silage ranged from 0.5% to 3% of the dry matter content. Ethanol emissions from silage are much greater than those of other compounds (Schmidt and Card, 2009; Mitloehner et al., 2009). According to Krauter et al. (2009), ethanol accounts for about 75% of total VOC emissions from silage sources. Based on model calculations, Howard et al. (2010) found that ethanol and other alcohols accounted for more than 50% of the ozone formation potential of VOC emissions from animal feeds in the San Joaquin Valley, California.

To estimate VOC emissions from various farm sources, generalized emission factors have been produced based on data derived from laboratory and farm measurements. Although it is known that emission rates vary with time, source characteristics, and environmental conditions (Zhang et al., 2009), generalized emission factors do not account for these sources of variation. When used to estimate VOC emissions, process-based models improve upon emission factors because they account for additional aspects that influence emission rates (NRC, 2003; Zhang et al., 2009). Hafner et al. (2009) developed a mathematical model for predicting VOC emission from the exposed surface of stored silage. Their model simulated diffusion in gas and aqueous phases through pores and silage particles, and convection from an exposed surface. Relationships used for predicting diffusion and mass transfer coefficients were based on correlations for smooth surfaces or relationships derived from work on soils (diffusion coefficients). These relationships have not been tested for silage.
In addition to environmental conditions, properties of silage itself influence VOC emission rates. In particular, “lightly packed” silage that has been removed from storage structures loses ethanol more rapidly than high-density silage present in storage structures (Hafner et al., 2010). Diffusion and mass transfer coefficients are affected by surface roughness created by particles on the silage surface. During animal feeding and preparation of feeds (e.g., total mixed ration), silage becomes lightly packed. The lightly packed silage has higher porosity and surface area than the silage held in storage structures, so higher emission rates of ethanol from the lightly packed silage could be expected. Therefore, quantification of ethanol emission from lightly packed silage is important. Hafner et al. (2010) used the logistic model of Demeyer et al. (1995) to simulate the cumulative ethanol emissions from lightly packed corn silage samples measured in a wind tunnel. Experiments were carried out on silage samples with a thickness of 150 mm at different temperatures (5°C to 35°C) and air velocities (0.06 to 5 m s⁻¹) as well as on a thin silage layer (30 mm thickness) at 20°C and 0.55 m s⁻¹. Good correlation between measured and predicted emissions from lightly packed corn silage was assumed. Therefore, development of a mass transfer model for ethanol emissions from a thin layer of corn silage under different temperatures and air velocities is still needed for predicting ethanol emissions. Therefore, the objectives of this work were to: (1) develop and evaluate a mathematical model for predicting ethanol emission from thin layers of corn silage exposed to moving air at different velocities and temperatures, and (2) experimentally determine the mass transfer coefficient under different air temperatures and velocities needed to predict VOC emissions from silage.

MATHEMATICAL MODEL FOR ETHANOL EMISSION

MODEL CONCEPT

A convective transport model was developed to predict ethanol emission from thin layers of silage. A first-order emission model in which ethanol flux is proportional to its volumetric concentration in the silage and varies with temperature and air velocity was assumed. In the proposed model, internal and external resistance is lumped with ethanol partitioning among solid and liquid phases to obtain an overall mass transfer coefficient.

The model concept is shown in figure 1. Ethanol was assumed to be emitted from the aqueous phase present in silage. The model was intended for predicting the emissions over a one-day period after exposing silage to air. Biochemical generation and consumption of ethanol was assumed to be negligible during the completion of the experiments. Therefore, a mass balance of ethanol in a thin layer of silage with uniform concentration exposed to moving air results in the following equation:

\[ V \frac{dC_s}{dt} = -AF \]  

where

\[ V = \text{volume of the silage layer (m}^3) \]
\[ C_s = \text{ethanol concentration in silage (kg m}^{-3}) \]
\[ t = \text{time the silage has been exposed to moving air (s)} \]

Figure 1. Schematic of a first-order mass transfer model for ethanol emissions from a thin layer of silage: \( K_L \) = overall mass transfer coefficient between bulk silage and atmosphere, \( C_s \) = ethanol concentration in bulk silage, and \( C_{amb} \) = ethanol concentration in ambient air.

\[ A = \text{exposed surface area of the silage layer (m}^2) \]
\[ F = \text{ethanol emission flux (kg m}^{-2} \text{s}^{-1}) \]

Using a mass transfer coefficient approach (Cussler, 1997), the emission flux of ethanol from bulk silage under different air temperatures and velocities was assumed to be proportional to the difference in ethanol concentrations between bulk silage and ambient air:

\[ F = K_L (C_s - C_{amb}) \]

Substituting the value of \( C_s - C_{amb} \) for \( \Delta C \) in equation 2 and applying the proportionality constant yields:

\[ F = K_L \Delta C \]

where

\[ K_L = \text{overall mass transfer coefficient of ethanol between bulk silage and ambient air (m s}^{-1}) \]

The values of \( K_L \) were estimated from laboratory experiments that are described later.

\[ C_s = \text{ethanol concentration in bulk silage (kg m}^{-3}) \]
\[ C_{amb} = \text{ethanol concentration in ambient air (kg m}^{-3}) \]

When the concentration of ethanol in ambient air is assumed negligible, equation 4 simplifies to:

\[ F = K_L C_s \]

And equation 1 becomes:

\[ V \frac{dC_s}{dt} = -K_L A C_s \]

Equation 7 is obtained after integrating equation 6, and it can be used to calculate the ethanol concentration \( C_s(t) \) in the silage as a function of initial ethanol concentration \( C_{s0} \) and exposure time \( t \):

\[ C_s = C_{s0} e^{-\frac{K_L A}{V} t} \]  

The overall mass transfer coefficient \( (K_L) \) was determined from data obtained in laboratory experiments as described later. This coefficient is an effective value that incorporates internal and external resistance and ethanol partitioning between the liquid and gas phases. The \( K_L \) parameter of the model presented in equation 7 was fitted to emission data obtained from experiments conducted in a wind tunnel system at several combinations of temperature and air velocity.

The model was evaluated using data obtained from a controlled environment chamber experiment. After evaluation, the model was used to predict ethanol emission from corn si-
lage on a farm located in the San Joaquin Valley, California. Air temperature and wind velocity for a typical day in July were used as inputs for the simulations. Simulations were carried out using Matlab (The Math Works, Inc., Natick, Mass.). Wind speed on the farm was measured using a sonic anemometer located at a height of 4.25 m \((h_1)\). To calculate the air velocity directly above the silage surface, assuming a zero plane displacement height to be zero, the following equation was used (Parker et al., 2008):

\[
V_{\text{silage}} = V_{\text{measured}} \left( \frac{\ln(h_2/h_0)}{\ln(h_1/h_0)} \right)
\]

where

\[
V_{\text{silage}} = \text{wind velocity over the silage surface (m s}^{-1})
\]

\[
V_{\text{measured}} = \text{wind velocity measured at height } h_1 \text{ (m s}^{-1})
\]

\[
h_2 = \text{height of the silage surface above the floor (assumed to be 0.2 m)}
\]

\[
h_0 = \text{roughness length calculated as 10\% } h_2 \text{ (Smith et al., 1988)}.
\]

Yanlian et al. (2006) defined roughness length as the height above a surface where the wind velocity calculated using the mean logarithmic wind profile equation approaches zero.

**EXPERIMENTAL WORK**

**DETERMINATION OF OVERALL MASS TRANSFER COEFFICIENT**

Wind tunnel experiments were conducted to determine the overall mass transfer coefficient \((K_t)\) for ethanol emission from thin layers of corn silage and to quantify the effects of temperature and air velocity on \(K_t\). Three temperatures \((15^\circ \text{C}, 25^\circ \text{C}, \text{and } 35^\circ \text{C})\) and three air velocities \((0.2, 1.5, \text{and } 2.5 \text{ m s}^{-1})\) were used in a 3\times3 factorial design with two replicates per treatment. Relative humidity was 70% for all trials.

After removing and discarding the outermost 100 mm, a corn silage sample (approx. 12 kg) was collected from a bunker silo face from a dairy farm in University Park, Pennsylvania. The silage was placed in two plastic bags and immediately transported to the laboratory, where the samples were stored at 2°C. After 3 h of cooling, the contents of the silage bags were thoroughly mixed in a large plastic container from which 200 ±0.5 g subsamples were weighed and placed in individual 3.8 L Ziploc bags. Mixing and sampling were done at 2°C inside a walk-in cold room to minimize volatilization of ethanol. Silage samples were stored at 2°C until they were used in the emission measurement trials. Before each trial, a bag containing a silage subsample was placed inside a small controlled environment chamber (length = 1.8 m, width = 0.76 m, height = 1.2 m) to equilibrate at the prescribed temperature for 30 min (for 15°C trials) or 1 h (for 25°C or 35°C trials). Before each trial started, the initial temperature of the sample was measured with an infrared thermometer. Starting temperatures were within 1.5°C of the desired temperature.

At the beginning of each trial, samples were evenly distributed within a 30 mm deep tray, the top of the wind tunnel system was attached to the top of the tray, and air flow and ethanol concentration measurements started. A detailed description of the experimental setup can be found in Montes et al. (2010). Each trial lasted 2 h and ended by dismantling the wind tunnel and returning the silage sample to its respective Ziploc bag to be weighed and stored frozen at -23°C.

During the measurement trials, three bags with silage subsamples were randomly selected and stored frozen at -23°C to determine the initial concentration of ethanol in the silage samples. Ethanol emission rate was calculated at each time step as the product of the mean airflow rate inside the wind tunnel and the vapor phase ethanol concentration in the wind tunnel (Hafner et al., 2010). Cumulative emission \((g \text{ ethanol kg}^{-1} \text{silage})\) was determined by numerically integrating the emission rate and dividing by the mass of the silage initially added in the chamber. The mass of ethanol remaining in the silage sample at each time step was calculated by difference, using a single average initial ethanol concentration for all samples.

**EMISSION MODEL EVALUATION EXPERIMENTS**

The emission model was evaluated using data from experiments conducted in a large controlled environment chamber (length = 10.5 m, width = 4.4 m, height = 2.8 m). Corn silage samples used in these experiments were collected in plastic bags from the corn silage pile of a commercial dairy farm in Woodland, California. Samples were collected after removing the outer 20 mm of the silage surface. After collection, silage bags were transferred to the laboratory and stored at 5°C until used in the experiments. A total of 100 kg of silage was evenly distributed to form a 40 mm thick layer on top of a 12.87 m² square plastic sheet located in the middle of the environmental chamber. Samples were collected to track ethanol concentration changes in the silage layer 5.0, 8.5, 18.5, and 24 h after the start of the experiment. At each sampling time, two silage samples (100 g each) were randomly collected from different locations on the silage layer. Prior to sample collection, the complete layer was manually mixed to attain a uniform ethanol concentration throughout the silage layer. Air was moved through the chamber at a rate of 2110 m³ h⁻¹ as measured by an airflow meter (Shortridge Instruments, Scottsdale, Ariz.). Ethanol concentration in the inflow and outflow was measured using a photoacoustic gas analyzer (Innova 1412, LumaSense Technologies, Ballerup, Denmark). Air velocity over the silage surface was measured in several locations using a hot-wire anemometer, and temperature inside the chamber was measured every minute using a HOBO sensor (Onset Computer Corp., Bourne, Mass.). The average air velocity measured directly above the silage (approx. 50 mm) was 0.24 m s⁻¹, and this value was used in model simulations. Ethanol emission rate and cumulative emission were calculated as described above for the wind tunnel.

**SILAGE ANALYSIS**

Ethanol, methanol, and VFAs were measured using a gas chromatograph (GC). Silage samples were diluted in water (1 silage: 9 water) and mixed for 30 min on a wrist action shaker (Burrell Corp., Pittsburgh, Pa.). The mixed samples were centrifuged for 10 min at 5000 rpm and then filtered using 0.45 μm membrane filters. The filtered samples were acidified using ortho-phosphoric acid (10%) to a pH < 2 before injection into the GC. The GC was equipped with a 530 μm inside diameter × 30 m long DB-wax capillary column (Agilent Technologies, Santa Clara, Cal.) and a flame ionization detector. Helium was used as a carrier gas at a flow rate of 5 mL min⁻¹. The oven temperature was increased from...
40 °C by 5 °C min⁻¹ to 60 °C, held for 1 min, and then increased by 25 °C min⁻¹ to a final temperature of 160 °C. Inlet and detector temperatures were set at 170 °C and 270 °C, respectively. Total solids (TS) content was determined by drying silage samples at 105 °C for 24 h to a constant weight. Volatile solids (VS) content was determined by combusting the dried samples at 550 °C for 2 h.

**DATA ANALYSIS**

Best-fit values of $K_L$ were estimated from ethanol concentration data obtained from the emission experiments conducted in the wind tunnel using the “nlinfit” routine in Matlab (The Math Works, Inc., Natick, Mass.) and equation 7. Multiple regression analysis was also conducted to determine the relationship between $K_L$ and temperature and air velocity.

**RESULTS AND DISCUSSION**

**SILAGE CHARACTERISTICS**

Characteristics of the corn silage used in the wind tunnel and environmental chamber experiments are shown in table 1. Ethanol and acetic acid were the most abundant compounds. The silage used in the environmental chamber experiment had a higher concentration of acetic acid and a lower concentration of ethanol than the silage used in the wind tunnel experiments. Differences between the two types of silage might be due to differences in the maturity of the corn used for silage production and production practices (Sheperd and Kung, 1996).

**ETHANOL EMISSIONS AND ESTIMATION OF OVERALL MASS TRANSFER COEFFICIENTS**

Ethanol emission increased with temperature and air velocity (fig. 2). The lowest cumulative emission was about 0.5 g kg⁻¹ of silage at 15 °C and 0.2 m s⁻¹, while the highest cumulative emission was about 3.9 g kg⁻¹ of silage at a temperature of 35 °C and air velocity of 2.5 m s⁻¹. Previous studies have also shown that ethanol emission from silage increases with temperature and air velocity (Montes et al., 2010; Hafner et al., 2010). These responses are consistent with a simple conceptual model of VOC emission from porous media, as described by Montes et al. (2010). A positive response to temperature is consistent with an increase in ethanol volatility, and a positive response to air velocity is consistent with an increase in convective mass transport from the silage surface due to a reduction in the boundary layer thickness (Arogo et al., 1999).

The ethanol concentration in the silage at each time step (i.e., 120 s) over the experimental time was calculated by subtracting the cumulative ethanol emissions per unit mass of silage over the elapsed time from the average measured initial ethanol concentration in the silage. The cumulative ethanol emission per unit mass of silage was calculated by integrating the measured emission rates over the elapsed time, divided by the amount of silage initially added in the wind tunnel in each experiment. The calculated ethanol concentrations in the silage were used to estimate the overall mass transfer coefficient in each experiment. In general, our model was able to fit experimental results closely; results from 15 °C and 0.2 m s⁻¹ and from 35 °C and 2.5 m s⁻¹ are shown in figure 3. The calculated $K_L$ values were 6.02 × 10⁻⁷ and 1.91 × 10⁻⁵ m s⁻¹ with $R^2$ values of 0.98 and 0.99, respectively. Best-fit values of $K_L$ increased with air velocity and silage temperature (fig. 4).

The following equation was obtained, from the multiple regression analysis, to calculate the overall mass transfer coefficient in the temperature range of 15 °C to 35 °C and air velocity range of 0.2 to 2.5 m s⁻¹:

$$K_L = 10^{-5} \left(0.0946 - 0.0017T - 0.3686V_{\text{silage}} + 0.0298TV_{\text{silage}}\right)$$

$R^2 = 0.952$  

![Figure 2. Cumulative ethanol emission after 2 h as measured in a wind tunnel. Error bars show standard deviations between duplicate experiments.](image2.png)

![Figure 3. Measured and predicted ethanol concentration in corn silage for wind tunnel experiments conducted at 15 °C and 0.2 m s⁻¹ and 35 °C and 2.5 m s⁻¹.](image3.png)

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**Table 1. Characteristics of corn silage used in wind tunnel and environmental chamber experiments.**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Wind Tunnel</th>
<th>Environmental Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Methanol</td>
<td>87.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>3720</td>
<td>236</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>2500</td>
<td>249</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>78.8</td>
<td>55.7</td>
</tr>
<tr>
<td>Iso-butyric acid</td>
<td>42.5</td>
<td>49.3</td>
</tr>
<tr>
<td>Butyric acid</td>
<td>64.7</td>
<td>67.6</td>
</tr>
<tr>
<td>Valeric acid</td>
<td>64.7</td>
<td>93.3</td>
</tr>
<tr>
<td>Total VFA</td>
<td>2850</td>
<td>350</td>
</tr>
<tr>
<td>pH</td>
<td>3.35</td>
<td>0.01</td>
</tr>
<tr>
<td>TS (% total mass)</td>
<td>34.5</td>
<td>1.8</td>
</tr>
<tr>
<td>VS (% of TS)</td>
<td>96.9</td>
<td>40.0</td>
</tr>
<tr>
<td>Bulk density (kg m⁻³)</td>
<td>297</td>
<td></td>
</tr>
</tbody>
</table>

[¹] Units for alcohols and VFAs are mg kg⁻¹ (wet basis).
where

\[ K_L = \text{mass transfer coefficient of ethanol (m s}^{-1}) \]
\[ T = \text{air temperature (°C)} \]
\[ V_{silage} = \text{air velocity over the silage surface (m s}^{-1}) \].

**MODEL EVALUATION**

The developed model could be applied to predict ethanol emissions from thin layers of silage exposed to air inside the environmental chamber. Predicted ethanol concentration and data measured in an environmental chamber experiment are shown in figure 5. Ethanol emission rate was calculated at each time step as the product of the mean airflow rate inside the environmental chamber and the vapor phase ethanol concentration. There was a good agreement between measured and predicted values obtained using the effective ethanol mass transfer coefficient calculated by equation 9.

There was a good agreement between measured cumulative ethanol emission in the environmental chamber experiments and values predicted by our model (fig. 6). After exposing the silage for one day inside the environmental chamber, the cumulative ethanol emission was 20 g m\(^{-2}\) (2.4 g kg\(^{-1}\) of silage).

The estimated mass transfer coefficient obtained in the wind tunnel experiments that lasted for 2 h worked well predicting ethanol emissions from the environmental chamber in which the silage was kept for one day. For thick silage layers, the decreased ethanol concentration on the surface promotes the transportation of ethanol within bulk silage via diffusion. The effect of diffusion and dispersion is expected to be minimal in the current experiments since thin layers of silage were used in the current experiments; thus, the factors affecting the overall mass transfer and initial ethanol concentration are the most important factors controlling the ethanol emission rate (refer to eq. 3). The overall mass transfer coefficient calculated here could be used when predicting ethanol emissions under similar conditions.

**PREDICTION OF ETHANOL EMISSION RATE UNDER DIFFERENT CONDITIONS**

The model was used to predict ethanol emission from corn silage having an initial ethanol concentration of 1.1 kg m\(^{-3}\) under different temperatures (15°C and 35°C) and air velocities (0.2, 1.25, and 2.5 m s\(^{-1}\)). Simulation results obtained at 35°C (fig. 7) indicate that at 1.25 and 2.5 m s\(^{-1}\) the majority of ethanol emission would occur within 5 h after the silage has been exposed to moving air, and that the emission rate decreases to less than 1% afterwards. At 0.2 m s\(^{-1}\), significant emission was still predicted after 15 h. Lower ethanol emission rates were predicted at a lower air temperature (15°C), as shown in figure 7. At 15°C, most ethanol was emitted within 20 h after exposing silage to air velocities of 1.25 and 2.5 m s\(^{-1}\), and at 0.2 m s\(^{-1}\) ethanol emission still occurred after one day. As shown in equation 3, our model assumes that ethanol emission is proportional to the initial ethanol concentration. Therefore, changes in the initial concentration will result in proportional changes in predicted emission rate and cumulative emission.

The proposed ethanol emission model was used to predict emission rates under conditions of a typical managed Californian dairy farm. Wind velocity and temperature were measured on a farm (fig. 8) at a height of 4.25 m and were used as input for simulation. Based on the assumption that the silage temperature will be equal to the air temperature, the measured air temperature and the air velocity over the silage surface were used to calculate the mass transfer coefficient.
Figure 7. Predicted ethanol emission rate from corn silage with 1.1 kg of ethanol per m$^3$ at different temperatures and air velocity.

The calculated value of the mass transfer coefficient was used to estimate the ethanol emission from a thin layer of silage on farm. Simulations started at 5:00 a.m. when the first animal feeding started. Simulations were performed for fresh corn silage taken directly from a silage pile (ethanol concentration = 1.1 kg m$^{-3}$) and for silage that had been exposed to air for 2 h and had lost 50% of the ethanol (ethanol concentration = 0.55 kg m$^{-3}$).

As expected, the simulation results indicate that ethanol emission rates are higher for higher initial ethanol concentrations, air temperature, and air velocity (fig. 9). Once the silage is exposed to air, ethanol emission occurs rapidly, with most of the ethanol lost within 24 h. The ethanol emission rate varies over time, being highest immediately after the silage is exposed to air and decreasing rapidly thereafter. Corn silage with 45% moisture content and an initial ethanol concentration of 1.1 kg m$^{-3}$ will lose most of the ethanol within the first 8 h when exposed to air velocities and temperatures ranging from 0.1 to 2.0 m s$^{-1}$ and 18$^\circ$C to 35$^\circ$C. Rates of ethanol emission from thin layers of corn silage ranged from 10 g m$^{-2}$ h$^{-1}$ to close to zero after 10 h of air exposure. Schmidt (2006) reported an ethanol flux in the range of 0.8 to 1 g m$^{-2}$ h$^{-1}$ from uncovered corn silage piles in two counties in California. The higher predicted ethanol emissions in the current study could be due to differences in the initial ethanol contents and wind velocities and temperatures. These parameters were not reported by Schmidt (2006). More farm measurement data, including emission rate, silage characteristics, and environmental conditions (i.e., wind velocity and silage and air temperatures), are needed in order to perform additional model evaluation under field conditions.

On the other hand, our model does not include the effect of physical properties that affect internal transport (e.g., silage porosity and sample depth) or ethanol partitioning (e.g., silage moisture content). Therefore, it may not be applicable for silage where these properties differ greatly from the samples used to develop the model. However, the model still provides an approximate estimate in these cases. For example, when cattle consume feed, the disturbance of the feed layer will reduce the internal resistance. In this case, it may be reasonable to assume that internal resistance is similar to that of a thin layer. This hypothesis needs to be tested in future work.

CONCLUSIONS

A mass transfer model was developed to predict ethanol emission from thin layers of corn silage exposed to open air. The model was evaluated using data collected from a controlled environmental chamber. The model was then used to simulate ethanol emission from thin layers of corn silage on a dairy farm in California’s San Joaquin Valley.
Greater ethanol emission rates occurred at higher silage temperatures and air velocities. After exposing a thin layer of silage (30 mm thickness) for 2 h in a wind tunnel, measured cumulative ethanol emissions ranged from 0.5 to 3.9 g kg⁻¹ silage, depending on temperature and air velocity. The lowest estimated $K_v$ value was $6.0 \times 10^{-7}$ m s⁻¹ at a temperature of $15$ °C and air velocity of 0.2 m s⁻¹, and the highest estimated $K_v$ value was $1.9 \times 10^{-5}$ m s⁻¹ at $35$ °C and 2.5 m s⁻¹. There was a good agreement between predicted and measured ethanol emission rates from the environmental chamber. Model predictions suggest that when silage is exposed to ambient conditions (temperature ranging from $16.1$ °C to $35.9$ °C and wind speed ranging from 0.1 to 2.2 m s⁻¹), most of the ethanol is emitted within 10 h. Predicted ethanol emission rates were as high as 10 g m⁻² h⁻¹ immediately after silage at $15$ °C was exposed to air flowing at 2.5 m s⁻¹, rapidly declining afterwards. Although the ethanol emission model from lightly packed silage was validated in an environmental chamber under controlled temperature and airflow conditions, more data under field conditions are needed to further validate the model.

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