

## RESEARCH ARTICLE OPEN ACCESS

# Chemical Composition and *In Sacco* Degradation Kinetics of Four Common Biowastes in Canterbury

Antonia S. E. Olszewski<sup>1</sup>  | Mancoba Mangwe<sup>2</sup>  | Brett Robinson<sup>3</sup>  | David Whitehead<sup>4</sup>  | Racheal H. Bryant<sup>1</sup> 

<sup>1</sup>Faculty of Agriculture and Life Sciences, Lincoln University, Lincoln, New Zealand | <sup>2</sup>DairyNZ, Lincoln University, Lincoln, New Zealand | <sup>3</sup>School of Physical and Chemical Sciences, University of Canterbury, Christchurch, New Zealand | <sup>4</sup>New Zealand Institute for Bioeconomy Science, Lincoln, New Zealand

**Correspondence:** Antonia S. E. Olszewski ([Antonia.Olszewski@lincolnuni.ac.nz](mailto:Antonia.Olszewski@lincolnuni.ac.nz))

**Received:** 13 June 2025 | **Revised:** 11 August 2025 | **Accepted:** 26 August 2025

**Keywords:** agri-food residues | by-product | feed evaluation | ruminant nutrition | waste-to-feed conversion

## ABSTRACT

This research aimed to quantify the chemical composition and rumen degradation kinetics of three local and one imported biowaste using the *in sacco* nylon bag technique. Triplicate samples of oven-dried biowastes ground to 4 mm were incubated in the rumens of four cows for 0 h, 2 h, 4 h, 6 h, 12 h, 24 h and 72 h. Bags attached to chains in descending order were placed in the ventral sac of the rumens. The soluble fractions (0 h) of dry matter were lowest for brewer's grains (BG) with  $8.4\% \pm 0.88\%$ , followed by palm kernel expeller (PKE) and potato waste (PW) with  $25.4\% \pm 0.27\%$  and  $29.9\% \pm 1.08\%$ , respectively. Apple pomace (AP) had the highest soluble fraction ( $54.7\% \pm 1.11\%$ ). For crude protein (CP), the rate of degradation was  $9.5\% \pm 1.0\%/h$  for BG,  $5.0\% \pm 1.1\%/h$  for AP,  $0.1\% \pm 0.0\%/h$  for PKE and  $21.1\% \pm 2.0\%/h$  for PW. These findings demonstrate the variability of local and imported biowastes and provide useful information on degradation kinetics which can be used for formulating diets.

## 1 | Introduction

Re-using horticultural biowastes as supplements in pastoral livestock systems may improve dietary nutrient use efficiency, fill pasture feed deficits, and reduce the carbon emissions intensity of animal products. In New Zealand (NZ), more than 2 million tonnes of food-processing biowastes are generated annually ([University of Canterbury 2021](#)). High volume examples suitable for livestock include apple pomace (AP) from the juicing industry (mainly of flesh, with some skins, stalks, and seeds), spent brewer's grains (BG) from beer production and potato waste (PW) which includes peeled offcuts of raw potatoes from chip production. Some biowaste supplements, such as palm kernel expeller (PKE), are imported and have high embedded emissions, largely from transportation. Using local supplements can help farmers meet low-emission incentive criteria set by Fonterra, while also improving rumen energy synchronisation through the diverse nutrient profiles of biowastes.

Variations in nutrient profiles impact both digestibility ([Kafilzadeh et al. 2008](#)) and efficiency of utilisation in the rumen. High fibre biowastes such as PKE and BG support rumen function, influencing digestibility. Biowastes high in sugars or starch like AP and PW provide energy for microbes, potentially improving the use of crude protein (CP) ([Zhang et al. 2020](#)). However, high sugar and starch levels also increase the risk of nutritional disorders such as acidosis, so typically form supplementation with pasture. Depending on the seasonal supply of biowastes, their value comes from potential use for balancing dietary requirements for energy, protein, or fibre. For example, in autumn, pasture often contains rapidly fermentable protein but is low in fermentable carbohydrates, increasing urinary N loss ([Bryant et al. 2012](#)); in such cases, low N biowastes could improve dietary N use.

Overseas research has investigated the rumen degradation kinetics of various biowastes, reporting wide variation in nutrient content and degradability both within and between different by-products. However, little is known about the nutrient content

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](#) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2026 The Author(s). *New Zealand Journal of Agricultural Research* published by John Wiley & Sons Australia, Ltd on behalf of Royal Society of New Zealand Te Apārangi.

or degradability of by-products in NZ. Therefore, this experiment aimed to quantify the chemical composition and rumen degradation kinetics, using the *in sacco* technique, of NZ-made AP, BG and PW compared to imported PKE for cows grazing pasture. We hypothesised that supplements high in fermentable carbohydrates (AP and PW) will provide the diet with suitable rumen energy synchrony that complements pasture.

## 2 | Materials and Methods

### 2.1 | Experimental Site and Design

The experiment was carried out at Ashley Dene Research and Development Station (43°38'48.16"S, 172°20'44.15"E) Springston, NZ, between the 5<sup>th</sup> and 15<sup>th</sup> of December 2023 with approval from the Lincoln University Animal Ethics Committee (AEC2023–30). The experiment was a crossover design with four biowastes over two runs using four cows per run.

### 2.2 | Materials

The AP, BG, PW and PKE were collected from commercial processors between 29 June 2023 and 2 November 2023. The AP, a by-product of juice production, was collected from Mill Orchard, Loburn; PW, offcuts from chip production, was collected from McCains, Timaru; and BG, a mix of spent grains following the malting process, was from DB Breweries, Timaru. These local biowastes were predominantly sourced from crops grown in Canterbury. The PKE was collected from Bunge, Rolleston, which imported the product. Local biowastes were initially stored at –20°C until oven drying at 60°C–65°C, ground to 4 mm, and stored in plastic bags.

### 2.3 | Nutrient Analysis

The particle size distribution of the biowastes was determined by sieving through a 2-mm stainless steel sieve. Each biowaste was ground to pass through a 1-mm sieve and analysed using wet chemistry methods. Nutrient analysis included water-soluble carbohydrates (WSC) and starch (Hunt et al. 2005). Lipids (AOAC 1990), nitrogen content by combustion (C/N series 828 Analyser, LECO, Michigan, USA), acid detergent fibre (ADF), neutral detergent fibre (NDF),  $\alpha$ -amylase neutral detergent fibre (aNDF) (Van Soest et al. 1991) and dry matter digestibility (DMD) (Clark et al. 1982). The  $\alpha$ -amylase fibre method was used only for the PW to remove the starch. Crude protein was estimated by multiplying N content by 6.25.

### 2.4 | Animals and In Sacco Procedures

Four rumen-cannulated Holstein  $\times$  Friesian non-lactating dairy cows with mean weight of 520  $\pm$  24 kg and age 3–4 years were used. Cows had a maintenance diet of 10–12 kg DM/cow/day consisting of a fresh daily allocation of (% DM, mean  $\pm$  SE) perennial ryegrass (*Lolium perenne* L., 79.3  $\pm$  9.1), white clover (*Trifolium repens* L., 7.5  $\pm$  5.3), weeds (monocotyledon 0.17  $\pm$  0.4, dicotyledon 7.3  $\pm$  6.7) and dead material (5.3  $\pm$  4.5). The nutrient composition of the basal diet was determined by calibrated near infrared spectroscopy (NIRS, Fossystems, Maryland) after sampling pasture to

grazing height each day, showing a metabolisable energy (ME) of 11.8  $\pm$  0.4 MJ/kg DM, CP of 11.5%  $\pm$  1.4%, NDF at 43.7%  $\pm$  4.3% and WSC of 27.2%  $\pm$  2.4%.

For the *in sacco* study,  $\approx$ 5 g DM of each dried biowaste, ground to 4 mm, was weighed in triplicate into nylon bags (105  $\times$  220 mm; 50  $\mu$ m pore size; Bar Diamond, Idaho, USA) and attached to one of four 0.7 kg stainless steel chains using zip ties. Each chain carried 36 bags (two biowastes and six incubation intervals) arranged in descending order so that bags requiring earlier removal were exposed first. Chains were soaked in warm water for 5–10 min before being placed into the ventral sac of the rumen for 2 h, 4 h, 6 h, 12 h, 24 h or 72 h. On sequential removal from each cow, bags were placed on one normal cold rinse cycle of a washing machine and then dried at 65°C for 24 h. Time-zero bags were not incubated but were soaked in warm water before washing and drying in the same manner as incubated bags. Residues were analysed for nitrogen concentration (C/N series 828 Analyser, LECO, Michigan, USA).

### 2.5 | Degradation Kinetics

Dry matter and crude protein disappearance data were fit to the exponential curves, as

$$D_{(DM,CP)} = a + b(1 - e^{(-k \times t)})$$

where  $D$  is the disappearance of dry matter and crude protein (%DM, CP),  $a$  is the soluble fraction (% DM, CP),  $b$  is the potentially degradable fraction (%DM, CP),  $k$  is the fractional disappearance rate (%/h), and  $t$  is the incubation time (h) (Ørskov and McDonald 1979). Model fitting was performed using R version 4.5.0.

Mean values from replicate bags were used for model fitting, except where bags met exclusion criteria. Bags were removed if integrity deteriorated during incubation, followed by cases where the coefficient of variation (CV) exceeded 5%. This led to the exclusion of 10 bags from BG, seven from PW and five from PKE. For the CP disappearance, many N values were at or below the analyser's detection limit, leading to large CVs. If protein disappearance within a replicate set was  $\leq -25\%$  and  $\geq 125\%$ , the bag with the value furthest from the mean was removed, resulting in five bags being removed for AP and one for PKE. Due to insufficient mass, PW samples after 12 h and AP samples after 24 h were pooled for a single N measurement. Effective degradability (ED) was calculated using

$$ED = a + \left( \frac{b \times k}{k + k_p} \right)$$

where  $a$ ,  $b$ , and  $k$  are the parameters estimated from fitting the disappearance data Equation (1), assuming three different rumen outflow rates ( $k_p$ ) of 5.05%/h, 6%/h and 7.5%/h. The undegradable fraction was calculated using

$$U = 100 - (a + b)$$

where  $U$  is the undegradable fraction,  $a$  is the soluble fraction and  $b$  is the potentially degradable fraction.

### 2.6 | Statistical Analysis

Degradation parameters were first estimated using a non-linear mixed-effects (NLME) model with restricted maximum likelihood

(REML) in the *nlme* R package. Models were fitted with and without fixed effects varying by biowastes for DM and CP disappearance, with cow included as a random effect; however, no notable random effects were found. Hence, the *nls2* R package (non-linear least squares (NLS)) was used to estimate fixed effects for each biowaste. Two-way ANOVAs, with cow and run as factors, were followed by post hoc Tukey tests to identify group differences. Despite using NLME and NLS and introducing lag period into each of these approaches, PKE failed to converge to an asymptote and best matched a linear relationship. Hence, estimated degradation rates and extents for PKE are unreliable; additional measurements beyond 72 h may help define the curve in future experiments.

### 3 | Results

The proportion of each biowaste passed through a <2-mm sieve was highest for PKE (93%) and lowest for PW (77%). Crude protein content of the biowastes was greatest for BG at over 20%, while both AP and PW contained less than 10% CP, and PKE fell in between (Table 1). The PW and AP were high in non-structural fractions and low in fibre fractions, while BG and PKE were the opposite. In vitro DMD ranged from the lowest of 36% for PKE to the highest of 97% for PW.

#### 3.1 | DM Digestion Kinetics

As with the nutrient composition, there was considerable variation in degradation characteristics among biowastes. The soluble fraction was greatest for biowastes high in sugars (AP) (Figure 1 and Table 2), though non-structural carbohydrate (NSC) content was a more important determinant of degradation rate which was greatest for PW, and slowest for PKE. Higher ADF content was generally associated with a larger undegradable fraction, although PKE had a lower fraction than BG despite its highest ADF content.

#### 3.2 | CP Digestion Kinetics

The CP soluble fraction for PW was more than twofold the value for PKE (Figure 2). Conversely, for AP, the soluble fraction was negligible, and the rate of degradation was slower compared to the other NZ biowastes. While the disappearance of protein in NZ biowastes was curvilinear, PKE was linear.

## 4 | Discussion

### 4.1 | Biowaste Nutrients

In this study, the nutritional content of PKE was similar to that reported by Dias et al. (2008); however, other biowastes were considerably different from those in other studies. The AP used here contained half the NDF and CP, but more than twofold NSCs compared to AP produced in Iran (Kafilzadeh et al. 2008). The Iranian AP was air-dried, a slower method that can reduce sugar content (Liang 2024). Additionally, BG used in an American study had higher CP (28.1%), lower NDF (54.0%) and higher starch (13.1%) (Batajoo and Shaver 1998), likely due to dissimilarities in the malting process. Such differences may also arise from cultivar selection, growing conditions, crop management, processing methods and preservation techniques (Kafilzadeh et al. 2008, Sveinbjörnsson et al. 2007). The biowastes in this study were oven-dried after collection to preserve samples prior to testing. In practice, farmers are likely to feed biowastes in their “raw” form. Further research on the effect of drying on the nutrient content of biowastes would improve confidence in feeding values.

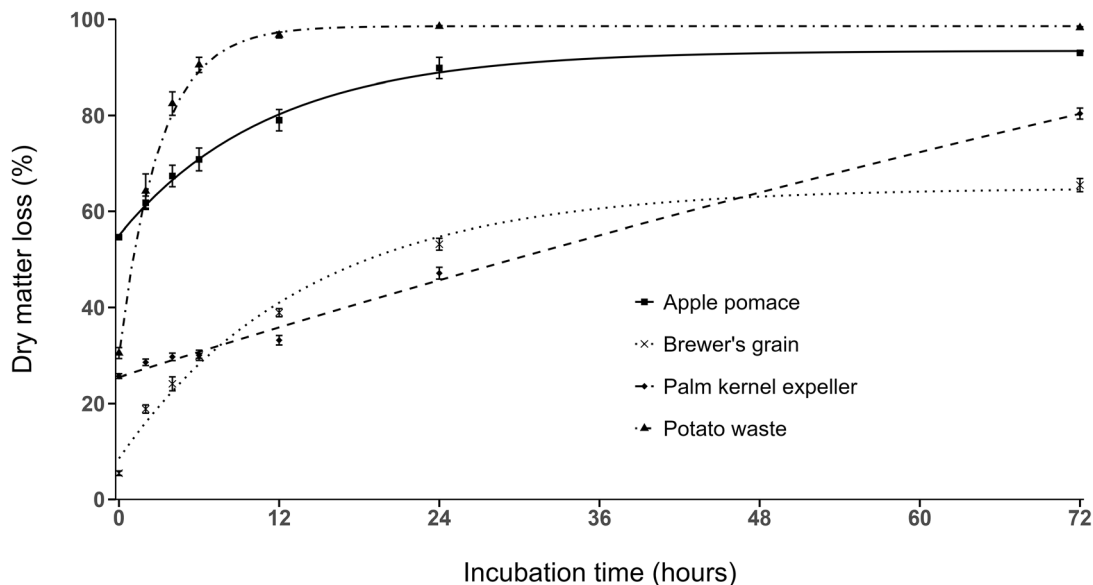
### 4.2 | DM Degradability of Biowastes

Our findings agree with previous research showing a negative relationship between degradation rate and fibre content (Kafilzadeh et al. 2008), with PKE as an exception. Although PKE had the highest proportion of hard-to-digest cellulose and lignin, it exhibited a higher potential extent of degradation than BG, which was lower in ADF. The PKE contained a higher

**TABLE 1** | Chemical composition (% of DM unless otherwise specified; mean  $\pm$  SE) of apple pomace (AP), brewer's grain (BG), potato waste (PW) and palm kernel expeller (PKE) used to quantify degradation kinetics and the pasture from the basal diet.  $n = 3$ .

	AP	BG	PW	PKE
Dry matter, % of FW	20.3 $\pm$ 1.1 <sup>c</sup>	23.8 $\pm$ 2.0 <sup>b</sup>	20.9 $\pm$ 3.9 <sup>c</sup>	96.8 $\pm$ 0.1 <sup>a</sup>
Organic matter	89.2 $\pm$ 0.1 <sup>c</sup>	89.4 $\pm$ 0.7 <sup>bc</sup>	90.3 $\pm$ 0.1 <sup>a</sup>	89.9 $\pm$ 0.2 <sup>abc</sup>
Crude protein	2.3 $\pm$ 0.3 <sup>d</sup>	21.1 $\pm$ 0.9 <sup>a</sup>	7.0 $\pm$ 0.2 <sup>d</sup>	16.8 $\pm$ 0.4 <sup>b</sup>
Acid detergent fibre	19.3 $\pm$ 0.3 <sup>c</sup>	26.5 $\pm$ 0.3 <sup>b</sup>	5.4 $\pm$ 0.5 <sup>d</sup>	40.8 $\pm$ 0.6 <sup>a</sup>
Neutral detergent fibre	27.0 $\pm$ 0.3 <sup>b</sup>	70.3 $\pm$ 1.1 <sup>a</sup>	7.14 $\pm$ 0.3 <sup>c</sup>	71.8 $\pm$ 0.4 <sup>a</sup>
Water-soluble carbohydrates	40.1 $\pm$ 1.3 <sup>a</sup>	1.5 $\pm$ 0.2 <sup>b</sup>	1.9 $\pm$ 0.2 <sup>b</sup>	2.5 $\pm$ 0.1 <sup>b</sup>
Starch	<0.1 $\pm$ 0.5 <sup>b</sup>	0.14 $\pm$ 0.7 <sup>b</sup>	14.7 $\pm$ 0.6 <sup>a</sup>	0.1 $\pm$ 0.3 <sup>b</sup>
Non-structural carbohydrates	69.0 $\pm$ 0.3 <sup>b</sup>	4.7 $\pm$ 0.4 <sup>d</sup>	82.7 $\pm$ 0.2 <sup>a</sup>	6.8 $\pm$ 0.4 <sup>c</sup>
Lipids	2.3 $\pm$ 0.1 <sup>c</sup>	6.6 $\pm$ 0.2 <sup>b</sup>	0.32 $\pm$ 0.0 <sup>d</sup>	7.7 $\pm$ 0.1 <sup>a</sup>
In vitro dry matter digestibility, %	85.1 $\pm$ 0.4 <sup>b</sup>	54.5 $\pm$ 0.2 <sup>c</sup>	96.7 $\pm$ 0.0 <sup>a</sup>	36.2 $\pm$ 0.3 <sup>d</sup>
Particle size < 2 mm, %	86.5 $\pm$ 0.3 <sup>b</sup>	80.1 $\pm$ 2.1 <sup>c</sup>	77.5 $\pm$ 0.5 <sup>c</sup>	92.7 $\pm$ 0.5 <sup>a</sup>

Note: Biowastes with different superscripts are different from each other ( $p < 0.05$ ).



**FIGURE 1** | *In sacco* fitted dry matter degradation curves fitted to the data for apple pomace (AP), brewer's grain (BG), potato waste (PW) and palm kernel expeller (PKE). Error bars indicate standard error.

**TABLE 2** | Estimates of dry matter and crude protein degradation parameters (% unless otherwise specified; mean  $\pm$  SE) for apple pomace (AP), brewer's grains (BG), potato waste (PW) and palm kernel expeller (PKE) defined as the soluble fraction (*a*), the potentially degradable fraction (*b*), the rate of degradation (*k*), the undegradable fraction (*U*) and the effective degradability (*ED*).

Parameter estimates				
Item	AP	BG	PW	PKE
<b>Digestion kinetics for dry matter disappearance</b>				
Soluble fraction	54.7 $\pm$ 1.1 <sup>a</sup>	8.4 $\pm$ 0.9 <sup>d</sup>	29.9 $\pm$ 1.1 <sup>b</sup>	25.4 $\pm$ 0.3 <sup>c</sup>
Potentially degradable fraction	38.9 $\pm$ 1.9 <sup>c</sup>	56.4 $\pm$ 2.2 <sup>b</sup>	68.7 $\pm$ 1.1 <sup>a</sup>	<sup>a</sup> 53.7 $\pm$ 2.4 <sup>b</sup>
Rate of degradation, %/h	9.6 $\pm$ 1.9 <sup>b</sup>	7.3 $\pm$ 0.4 <sup>c</sup>	33.6 $\pm$ 3.2 <sup>a</sup>	0.04 $\pm$ 0.0 <sup>c</sup>
Potential extent of degradation	93.6 $\pm$ 0.9 <sup>a</sup>	64.8 $\pm$ 1.8 <sup>c</sup>	98.6 $\pm$ 0.1 <sup>a</sup>	79.2 $\pm$ 2.3 <sup>b</sup>
Undegradable fraction <sup>b</sup>	6.4 $\pm$ 0.9 <sup>c</sup>	35.2 $\pm$ 1.8 <sup>a</sup>	1.4 $\pm$ 0.1 <sup>c</sup>	20.8 $\pm$ 2.3 <sup>b</sup>
Effective degradability <sup>c</sup> (slow)	79.5 $\pm$ 1.2 <sup>b</sup>	41.6 $\pm$ 0.4 <sup>c</sup>	89.5 $\pm$ 0.6 <sup>a</sup>	<sup>d</sup> 29.4 $\pm$ 2.0 <sup>d</sup>
Effective degradability <sup>c</sup> (medium)	77.9 $\pm$ 1.3 <sup>b</sup>	39.2 $\pm$ 0.4 <sup>c</sup>	88.1 $\pm$ 0.7 <sup>a</sup>	<sup>d</sup> 28.9 $\pm$ 1.7 <sup>d</sup>
Effective degradability <sup>c</sup> (fast)	75.9 $\pm$ 1.4 <sup>b</sup>	36.1 $\pm$ 0.4 <sup>c</sup>	85.9 $\pm$ 0.8 <sup>a</sup>	<sup>d</sup> 28.3 $\pm$ 0.8 <sup>d</sup>
<b>Digestion kinetics for crude protein disappearance</b>				
Soluble fraction	-10.6 $\pm$ 3.1 <sup>d</sup>	8.8 $\pm$ 6.9 <sup>c</sup>	66.7 $\pm$ 3.8 <sup>a</sup>	25.1 $\pm$ 3.9 <sup>b</sup>
Potentially degradable fraction	<sup>a</sup> 105.7 $\pm$ 2.7 <sup>a</sup>	75.3 $\pm$ 10.8 <sup>b</sup>	29.7 $\pm$ 3.4 <sup>c</sup>	<sup>a</sup> 68.1 $\pm$ 4.1 <sup>b</sup>
Rate of degradation, %/h	5.0 $\pm$ 1.1 <sup>b</sup>	9.5 $\pm$ 1.0 <sup>b</sup>	21.1 $\pm$ 2.0 <sup>a</sup>	0.1 $\pm$ 0.0 <sup>b</sup>
Potential extent of degradation	95.0 $\pm$ 1.5 <sup>ab</sup>	84.2 $\pm$ 4.1 <sup>b</sup>	96.4 $\pm$ 0.7 <sup>a</sup>	93.1 $\pm$ 1.0 <sup>ab</sup>
Undegradable fraction <sup>b</sup>	5.0 $\pm$ 1.5 <sup>ab</sup>	15.8 $\pm$ 4.1 <sup>a</sup>	3.6 $\pm$ 0.7 <sup>b</sup>	6.9 $\pm$ 1.0 <sup>ab</sup>
Effective degradability <sup>c</sup> (slow)	40.4 $\pm$ 5.5 <sup>c</sup>	58.3 $\pm$ 2.0 <sup>b</sup>	90.7 $\pm$ 1.0 <sup>a</sup>	<sup>d</sup> 25.9 $\pm$ 3.8 <sup>c</sup>
Effective degradability <sup>c</sup> (medium)	36.0 $\pm$ 5.4 <sup>c</sup>	55.4 $\pm$ 1.8 <sup>b</sup>	89.8 $\pm$ 1.1 <sup>a</sup>	<sup>d</sup> 25.7 $\pm$ 3.8 <sup>c</sup>
Effective degradability <sup>c</sup> (fast)	30.5 $\pm$ 5.2 <sup>c</sup>	51.3 $\pm$ 1.6 <sup>b</sup>	88.6 $\pm$ 1.2 <sup>a</sup>	<sup>d</sup> 25.6 $\pm$ 3.8 <sup>c</sup>

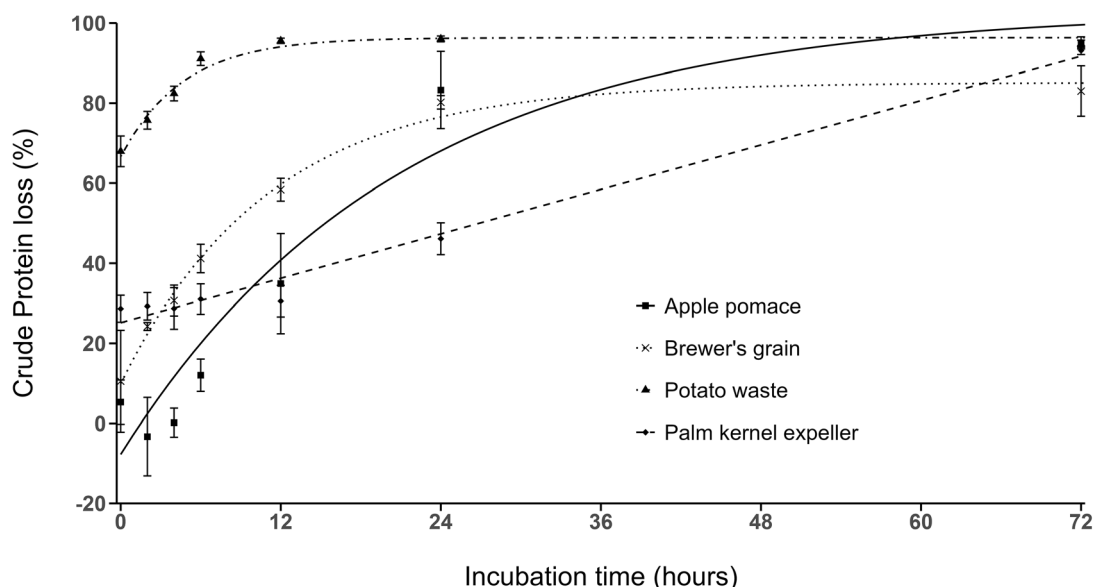
Note: Biowastes with different superscripts are different from each other ( $p < 0.05$ ).

<sup>a</sup>Potentially degradable fraction was calculated as "maximum recorded mean" (MRM) - soluble fraction".

<sup>b</sup>Undegradable fraction was calculated as (100 - (soluble fraction + potentially degradable fraction)) except for PKE (DM and CP) and AP (CP) which was (100 - 'MRM').

<sup>c</sup>ED was calculated as soluble fraction + (potentially degradable fraction  $\times$  rate of degradation)/(rate of degradation +  $k_p$ ) where  $k_p$  was 5.05%/h, 6.00%/h and 7.5%/h.

<sup>d</sup>ED was calculated using the MRM.



**FIGURE 2** | *In sacco* fitted crude protein degradation curves fitted to data for apple pomace (AP), brewer's grain (BG), potato waste (PW) and palm kernel expeller (PKE). Error bars indicate standard error.

proportion of particles less than 2 mm (93%) compared to BG (86%), increasing surface area and microbial adhesion which is critical for the breakdown of nutrients (Dias et al. 2008). Alternatively, the amount and association of lignin to cellulose may differ between palm and barley husks which could influence degradability.

The rate of degradation contrasted widely among our biowastes. The PW degraded quickest due to the high NSC and low NDF, whereas BG degraded slowly due to its high NDF and low NSC. The rates of DM degradation of AP and BG were similar to those reported in the literature (5%/h juice AP; 8%/h puree AP (Kafilzadeh et al. 2008) and 5%/h (Batajoo and Shaver 1998) respectively). However, the PW disappearance rate differed from Hindle et al. (2005) (6.3%/h). Their PW contained 32% NDF which is more than fourfold higher than the PW used in this study, reflecting both the heating effect during drying which can increase starch degradability (Sveinbjörnsson et al. 2007), and the higher proportion of fibre-rich potato skins.

### 4.3 | CP Degradability of Biowastes

The rate of protein degradation plays an important role in nutrient use efficiency. Feeds high in soluble CP but lacking sufficient fermentable energy are prone to N loss as urinary urea. In this study, degradation rates varied widely among biowastes with the most rapid being the PW which was 75% degraded within 2 h. Conversely, BG required 20 h to reach the same extent. This rapid degradation suggests that ruminants supplemented with PW may have excreted most of the N via urine. However, because BG has threefold more CP than PW, higher urinary excretion would still be expected in animals supplemented with BG due to higher N intake.

The soluble fraction for AP was negative which is unusual as it suggests N gain during the rinsing step. The negative value may instead reflect the low initial N content, potentially below the C/N analyser's detection limit. As the analysis reports N as a proportion of total mass, removal of WSCs (which appeared to

contain negligible N) could have increased the relative N concentration.

## 5 | Conclusions

This study quantified the DM and CP degradation kinetics of NZ-produced AP, BG, and PW in cows fed solely pasture; however, PKE kinetics could not be determined due to insufficient data beyond 72 h of incubation. Future research should examine tailored biowaste mixtures to optimise energy-nitrogen synchrony and assess how processing and preservation affect nutrient composition. Overall, biowastes can replace PKE as supplementary feeds when available, reducing reliance on high-emission products, improving grazing-system sustainability and, in some cases, enhancing rumen synchrony.

### Acknowledgements

We thank the staff at the biowaste processing outlets for supplying the feeds. We are grateful to Nimisha Subash and Finn O'Keeffe for bag preparation assistance; to Lucas Tey and Paige Beckett for experimental help; to Dean O'Connell, Jasmine Tanner, and David Baird for statistical advice; to Shuang Jiang, Rosy Tung, and Rob Stainthorpe for laboratory support; and to OpenAI's GPT-5 (ChatGPT) for assistance in meeting the word limit.

Open access publishing facilitated by Lincoln University, as part of the Wiley-Lincoln University agreement via the Council of Australian University Librarians.

### Funding

This work was supported by the Food Transitions 2050.

### References

AOAC. 1990. *Fibre (Acid Detergent) and Lignin in Animal Feed 973.18 Official Methods of Analysis*. Association of Official Analytical Chemists.

- Batajoo, K. K., and R. D. Shaver. 1998. "In Situ Dry Matter, Crude Protein, and Starch Degradabilities of Selected Grains and By-Product Feeds." *Animal Feed Science and Technology* 71: 165–176.
- Bryant, R. H., P. Gregorini, and G. R. Edwards. 2012. "Effects of N Fertilisation, Leaf Appearance and Time of Day on N Fractionation and Chemical Composition of Lolium Perenne Cultivars in Spring." *Animal Feed Science and Technology* 173: 210–219.
- Clark, T., P. C. Flinn, and A. A. McGowan. 1982. "Low Cost Pepsin-Cellulase Assays for Prediction of Digestibility of Herbage." *Grass and Forage Science* 37: 147–150.
- Dias, F. N., J. L. Burke, D. Pacheco, and C. W. Holmes. 2008. "In Sacco Digestion Kinetics of Palm Kernel Expeller (Pke)." *Proceedings of the New Zealand Grassland Association* 70, pp. 259–264.
- Hindle, V. A., A. M. Vuuren Van, A. Klop, A. A. Mathijssen-Kamman, A. H. Van Gelder, and J. W. Cone. 2005. "Site and Extent of Starch Degradation in the Dairy Cow – a Comparison between In Vivo, In Situ and In Vitro Measurements." *Journal of Animal Physiology and Animal Nutrition* 89: 158–165.
- Hunt, M. G., S. Rasmussen, P. C. D. Newton, A. J. Parsons, and J. A. Newman. 2005. "Near-Term Impacts of Elevated Co<sub>2</sub>, Nitrogen and Fungal Endophyte-Infection on Lolium Perenne L. Growth, Chemical Composition and Alkaloid Production." *Plant, Cell & Environment* 28: 1345–1354.
- Kafilzadeh, F., G. Taasoli, and A. Maleki. 2008. "Kinetics of Digestion and Fermentation of Apple Pomace from Juice and Puree Making." *Research Journal of Biological Sciences* 10: 1143–1146.
- Liang, Y. 2024. "Different Drying Methods' Effects on the Nutritional Components and Flavor of Fruits." *Journal of Food and Drug Safety Research* 1, <https://doi.org/10.70767/jfdr.v1i2.227>.
- Ørskov, E. R., and I. McDonald. 1979. "The Estimation of Protein Degradability in the Rumen from Incubation Measurements Weighted According to Rate of Passage." *The Journal of Agricultural Science* 92: 499–503.
- Sveinbjörnsson, J., M. Murphy, and P. Udén. 2007. "In Vitro Evaluation of Starch Degradation from Feeds with or without Various Heat Treatments." *Animal Feed Science and Technology* 132: 171–185.
- University of Canterbury. 2021. New Kiwi Research to Turn Biowaste into Economic Boost. University of Canterbury <http://www.canterbury.ac.nz/news/2021/new-kiwi-research-to-turn-biowaste-into-economic-boost-.html> [accessed 4 February 2023]. (2021).
- Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. "Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to Animal Nutrition." *Journal of Dairy Science* 74: 3583–3597.
- Zhang, J., N. Zheng, W. Shen, S. Zhao, and J. Wang. 2020. "Synchrony Degree of Dietary Energy and Nitrogen Release Influences Microbial Community, Fermentation, and Protein Synthesis in a Rumen Simulation System." *Microorganisms* 8: 231.