

ABSTRACT

The rapid expansion of the dairy industry generates large volumes of organic waste, including wastewater, whey, and sludge. In arid regions such as Qatar, managing these wastes is challenging due to water scarcity, limited land, and high temperatures. Conventional disposal methods contribute to greenhouse gas emissions and environmental degradation. Anaerobic digestion (AD) offers an effective solution for treating high-strength waste while producing renewable biogas; however, the resulting digestate requires further stabilization. Composting provides a sustainable post-treatment by converting digestate into nutrient-rich biofertilizer. This study proposes an integrated anaerobic digestion-composting (IADC) system for dairy waste management in arid climates, enhancing both energy and material recovery while supporting circular economy principles and Qatar National Vision 2030.

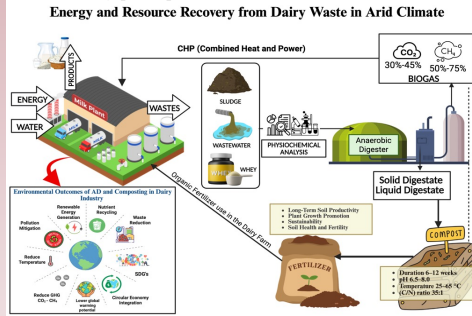


Figure 1. Graphical abstract of Anaerobic digestion and composting of Dairy waste.

RESEARCH OBJECTIVE

1. Characterize whey, CIP, and FC wastewater.
2. Evaluate biodegradability and composition.
3. Compare methane production potential.
4. Identify strategies for efficient resource recovery.

MATERIALS AND METHOD

Samples collection

Whey, CIP wastewater, and floor-cleaning (FC) wastewater were collected from a dairy facility in Qatar. Samples were stored at 4 °C and analyzed within 24 hours. Prior to analysis, samples were mixed thoroughly. All tests were conducted in duplicate (n = 2), and results are reported as mean ± standard deviation.

Physicochemical Characterization

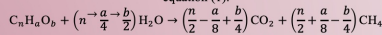
Physicochemical parameters including pH, electrical conductivity, turbidity, and total suspended solids (TSS/VSS) were analyzed using standard methods. Organic content was assessed through total and soluble COD, TOC, and TN, while volatile fatty acids (VFAs) and major anions were determined using ion chromatography. Elemental composition was analyzed using ICP-OES to evaluate nutrient availability and potential inhibition in anaerobic digestion.

Theoretical yield of Biogas

Theoretical methane production per unit volume of wastewater was calculated using the COD-based Buswell stoichiometry, which relates organic matter oxidation to methane production under anaerobic conditions:

$$V_{CH_4} = \frac{tCOD \times 0.35}{1000}$$

where V_{CH_4} = theoretical methane volume ($m^3 CH_4/m^3$ wastewater), tCOD = total chemical oxygen demand (mg/L), and 0.35 L CH_4/g COD is the theoretical methane yield at standard temperature and pressure (STP: 0 °C, 1 atm) derived from the Buswell equation (1):



At 80% COD removal efficiency (a realistic operational target for high-rate AD systems), the achievable methane volume was calculated as:

$$V_{CH_4,80\%} = V_{CH_4} \times 0.80$$

RESULTS AND DISCUSSION

BOD₅ Estimation and BOD₅/COD Ratios

Table 1. Biodegradability indicators and nutrient stoichiometry

Parameter	Whey	CIP WW	FC WW
sCOD/tCOD	0.99	0.47	0.98
BOD ₅ (mg/L)	5,240	169.1	7.2
BOD ₅ /COD	0.138	0.029	0.133
P (mg/L)	6,026.7	14.38	0
COD:N	397:1	387:1	51:1
COD:P	6.3:1	408.9:1	N/A

Nutrient Stoichiometry: COD:N:P Ratios

ACKNOWLEDGMENT AND REFERENCES

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1. Buswell, A. M., & Mueller, H. F. (1952). Mechanism of methane fermentation. Industrial & Engineering Chemistry, 44(3), 550–552. <https://doi.org/10.1021/i350507a033>

RESULTS AND DISCUSSION

Physicochemical Characterisation

Table 1. Comprehensive physicochemical, organic, anion, elemental, and methane characteristics of dairy processing streams (mean ± SD, n = 2)

Parameter	Whey	CIP Wastewater	FC Wastewater
pH	3.41 ± 0.00	7.18 ± 0.02	7.20 ± 0.00
Total COD (mg L ⁻¹)	38,000 ± 905	5,880 ± 1,005	54 ± 6
Soluble COD (mg L ⁻¹)	37,620 ± 198	2,785 ± 120	53 ± 1
TOC (mg L ⁻¹)	5,112 ± 102	165 ± 1	7.0 ± 0.3
TN (mg L ⁻¹)	95.7 ± 1.4	15.2 ± 0.0	1.06 ± 0.03
IC (mg L ⁻¹)	7.03 ± 0.38	27.06 ± 1.10	10.5 ± 0.1
TSS (mg L ⁻¹)	968 ± 6	613 ± 25	3 ± 1
Turbidity (NTU)	477 ± 4	1226 ± 7	7.37 ± 0.03
VFAs (mg L ⁻¹)			
Lactate	849 ± 24	58 ± 74	ND
Formate	ND	0.56 ± 0.78	ND
Acetate	63.3 ± 8.8	0.94 ± 1.02	ND
Butyrate	10.8 ± 1.8	89.2 ± 78.8	23.2 ± 2.9
Malate	18,227 ± 114	ND	ND
Major Anions (mg L ⁻¹)			
Chloride	ND	103.8 ± 5.9	41.2 ± 4.7
Nitrate	384.5 ± 1.4	50.9 ± 0.14	7.42 ± 0.05
Phosphate	18,481 ± 356	44.1 ± 0.57	ND
Sulfate	3,383.5 ± 43.8	12.1 ± 0.49	16.5 ± 1.4
Bromide	348.0 ± 2.1	5.6 ± 0.0	ND
Fluoride	28,148.8 ± 457	ND	ND
Macro-elements (mg L ⁻¹)			
Sodium	19,220 ± 1,400	43.4 ± 4.0	25.9 ± 0.1
Calcium	918 ± 4	48.1 ± 4.4	13.2 ± 0.2
Potassium	805 ± 106	38.8 ± 2.2	2.23 ± 0.13
Magnesium	58 ± 4	4.84 ± 0.55	1.02 ± 0.01
Zinc	10 ± 0	0.07 ± 0.02	0.01 ± 0.00

ND = Not detected

Biodegradability Indicators

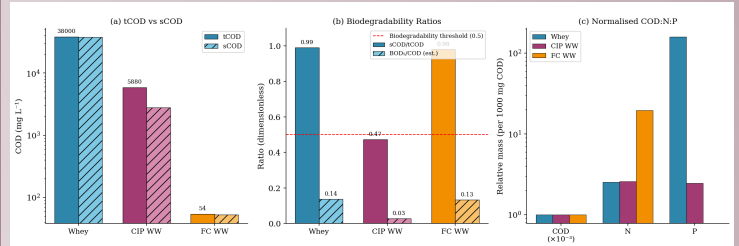


Figure 2. Organic Characterisation and Biodegradability Indicators

Methane Potential

Theoretical Methane Yield Calculations

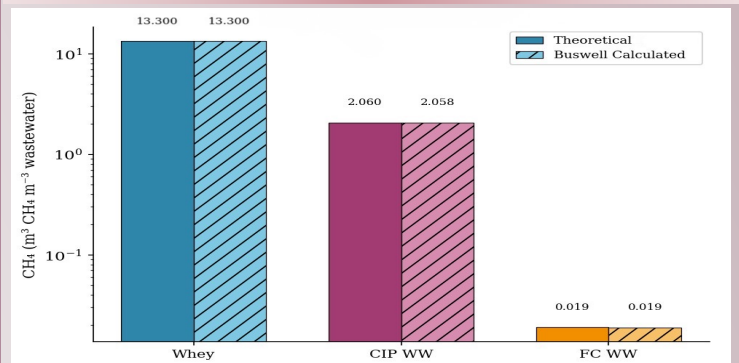


Figure 3. Theoretical vs Buswell-Calculated CH₄

CONCLUSION

Stream-specific analysis is essential for optimizing dairy wastewater treatment. Whey shows high methane potential but requires control of salinity and nutrients, while CIP needs pretreatment and FC serves as a dilution stream. Overall, co-digestion and proper stream segregation significantly improve process stability and energy recovery.

Environmental Benefits of Integration Anaerobic digestion and Composting

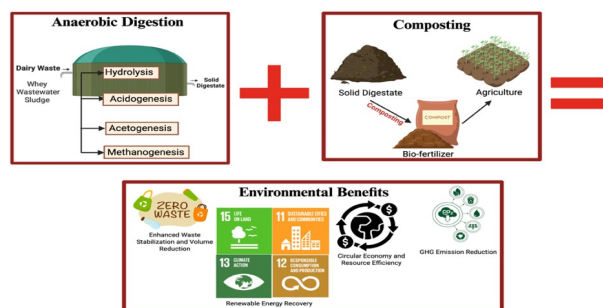


Figure 4. Environmental Benefits of Integrated system (AD-composting).