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A simplified compartmental model for assessing nitrogen flows and losses in dairy effluent management systems: evidence from intensive farms in the Po Valley (Italy)

Giulia Ferronato[1]*, Anna Simonetto[1], Valentina Caprarulo[2], Elena Scaglia[1] and Gianni Gilioli[1]

[1]Department of Civil Engineering, Architecture, Environment, Land Planning and Mathematics (DICATAM), Università degli Studi di Brescia, Brescia, Italy, [2]Istituto Zooprofilattico Sperimentale della Lombardia e dell'Emilia Romagna "Bruno Ubertini", Brescia, Italy

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Daniela Lovarelli,
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Universidad Autónoma de Tamaulipas,
Mexico

*CORRESPONDENCE
Giulia Ferronato
✉ giulia.ferronato@unibs.it

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Introduction: Nitrogen management in dairy production systems is a major determinant of environmental performance and nutrient use efficiency, as substantial nitrogen losses can occur along the manure management chain. Although life cycle assessment and nutrient balance approaches are commonly used to estimate emissions, they often provide limited insight into internal nitrogen transformations and provide restricted support for farm-scale decision making. This study aimed to develop a simplified compartmental model to quantify nitrogen flows and losses across the main components of intensive dairy farms.
Methods: The model combines process-based relationships with a limited set of farm-specific input data, including herd composition, feeding strategy, housing systems, and manure management practices. Nitrogen dynamics are represented through interconnected compartments describing the animal, barn, treatment, storage, and land application phases, enabling the identification of key stages contributing to gaseous nitrogen losses. The model was applied to ten commercial Holstein dairy farms located in the Po Valley (Northern Italy).
Results: Total gaseous nitrogen losses averaged 7.20 ± 6.43% of nitrogen intake in untreated systems, with ammonia volatilization representing the dominant loss pathway. Farms adopting anaerobic digestion showed increased nitrogen retention in digestate, despite higher overall losses associated with subsequent handling stages. A preliminary comparison between simulated and measured nitrogen concentrations in selected manure and digestate matrices indicated a generally consistent representation of nitrogen partitioning, although systematic overestimations were observed for liquid matrices during the early management stages.
Discussion: Given the limited number of monitored farms and the absence of a comprehensive quantitative validation, the results should be interpreted as indicative of nitrogen flow patterns rather than precise emission estimates. Nevertheless, the proposed framework provides a transparent and data-efficient tool for exploring farm-specific nitrogen balances, supporting scenario analyses and nutrient management strategies, and contributing to the transition toward more circular and environmentally efficient dairy production systems.

KEYWORDS
dairy system, nitrogen, nitrogen emissions, nutrient circularity, nutrient flow

1 Introduction

The dairy sector plays a fundamental role in food production and rural economies worldwide but is increasingly scrutinized for its environmental impacts, particularly those associated with greenhouse gas (GHG) emissions and nutrient losses from manure management. Nitrogen (N) is a key nutrient underpinning agricultural productivity and human nutrition; however, its inefficient use in livestock systems can result in substantial environmental impacts. In ruminant production systems, plant-derived proteins are converted, together with microbial protein synthesized in the rumen, into high biological-value proteins in milk and meat. Nevertheless, a considerable proportion of ingested nitrogen is not retained in animal products and is instead excreted in feces and urine (Castillo et al., 2000; Kebreab et al., 2001).

Following excretion, nitrogen enters the manure management chain, including housing, storage, treatment, and land application, where it undergoes a series of physical, chemical and microbial transformations (O'Brien and Hatfield, 2019; Owen and Silver, 2015; Wattiaux et al., 2019). These processes determine the partitioning of nitrogen between recyclable nutrient pools and environmentally reactive forms. When effectively recovered and recycled, livestock excreta can represent a valuable nutrient source for crop production, contributing nutrient circularity and reducing dependence on mineral fertilizers (Zhang et al., 2021). Conversely, inadequate management may lead to nitrogen losses in several forms, including organic compounds, ammonia (NH_3), nitrous oxide (N_2O), dinitrogen (N_2), and nitrate (NO_3^-), contributing to air pollution, eutrophication, acidification, biodiversity loss, and climate change.

Achieving effective nutrient circularity, however, requires a detailed understanding of nitrogen transformations and transfer processes throughout the farm system (Beukes et al., 2017; Børsting et al., 2003). However, reliable quantification of these nitrogen dynamics remains challenging. Direct measurements are often costly, time-consuming, and highly variable across farms and seasons (Cabrera et al., 2006; Ramírez and Reheul, 2009). Moreover, nitrogen fluxes in livestock systems are governed by complex and dynamic interactions among animal physiology, diet composition, housing conditions, manure handling practices, treatment technologies, and environmental drivers. Reliable estimation of nitrogen excretion, transformation, and loss is therefore essential not only for environmental reporting and regulatory compliance, but also for improving nutrient use efficiency and nutrient recycling at farm level (Velthof et al., 2015).

To date, the environmental assessment of dairy systems has largely relied on Life Cycle Assessment (LCA) approaches, which quantify emissions and resource use across production stages and are widely used to estimate carbon footprints (Notarnicola et al., 2017). Although LCA provides a valuable overview of system-level environmental impacts, it mainly reports aggregated outputs and emissions, offering limited insight into internal nutrient dynamics occurring within the farm and into the identification of critical control points for mitigation (Hetherington et al., 2014; Rufí-Salís et al., 2021). Consequently, the ability of LCA to support farm-level decision-making aimed at improving nutrient use efficiency (NUE) and closing nutrient cycles remains limited (Powell et al., 2010).

Nutrient balance approaches provide an alternative framework for quantifying nutrient inputs, outputs and internal flows within agricultural systems. When systematically applied, nutrient budgets can serve as effective diagnostic and management tools for improving efficiency and reducing losses (Öborn et al., 2003). However, existing accounting approaches differ substantially in their structure, level of detail, and data requirements, ranging from simple empirical calculators to complex process-based models (Casson et al., 2023; Goodlass et al., 2003). However, existing accounting approaches differ substantially in their structure, level of detail, and data requirements, ranging from simple empirical calculators to comprehensive process-based models such as the Integrated Farm System Model (IFSM) (Rotz, 2004). and the Cornell Net Carbohydrate and Protein System (CNCPS)-based nutrient balance framework (Dou et al., 1996). While these models provide valuable insights into nutrient dynamics, they are often calibrated for specific production contexts or require extensive datasets that are not always available under commercial farming conditions, thereby limiting their broader applicability (Cabrera et al., 2006; Dou et al., 1996; Rotz, 2004).

These limitations highlight the need for modelling approaches capable of combining mechanistic representations of nitrogen processes with practical applicability at farm scale. In particular, there is increasing interest in flexible frameworks that integrate process-oriented descriptions of nitrogen transformations with the limited data typically available on commercial farms (Ndegwa et al., 2008; Oenema et al., 2007). Such tools can improve the understanding of nitrogen dynamics along the manure management chain, support the identification of major emission pathways, and facilitate the evaluation of alternative management strategies.

In this context, this study proposes a simplified compartmental model designed to quantify nitrogen flows and losses across the main components of intensive dairy farms. The research question addressed is whether a simplified process-based compartmental model, relying on a limited set of farm-specific input data, can provide reliable estimates of nitrogen partitioning and losses along the manure management chain. We hypothesize that such an approach can capture the main nitrogen transformation processes with sufficient accuracy to support farm-scale nutrient assessments while remaining practical for commercial farming conditions. The model integrates process-based relationships with a limited number of farm-specific input variables describing herd composition, feeding practices, housing characteristics, and manure management systems. The framework aims to provide a transparent and data-efficient tool for assessing nitrogen partitioning along the manure management chain, supporting farm-scale analyses of nutrient conservation, emission patterns, and management scenarios. The model was applied to ten commercial dairy farms located in the Po Valley (Northern Italy), one of the most intensive livestock production areas in Europe, and its outputs were compared with measured nitrogen concentrations in selected manure and digestate matrices to perform a preliminary evaluation of model performance.

2 Materials and methods

The following section describes the modelling framework developed to quantify nitrogen flows and emissions along the effluent management chain in dairy farms, the farm-level data used as model inputs, and the procedure adopted for the preliminary evaluation of model performance.

2.1 Simplified compartmental dairy farm model

A simplified compartmental model was developed to quantify nitrogen flows and emissions across the main stages of effluent management in dairy farms. Following the mass-flow approach proposed by Webb and Misselbrook (2004), the model represents the farm as a set of interconnected compartments corresponding to animal excretion, housing, treatment, storage, and land application (Figure 1).

Model coefficients were obtained primarily from EEA (2019a, 2019b), IPCC (2019), de Vries et al. (2020), and Webb and Misselbrook (2004), and are reported within the description of the individual compartments.

The main assumptions of the model were: (i) steady-state conditions throughout the simulation period; (ii) homogeneous mixing within each compartment; (iii) annual-average representation of effluent management practices; and (iv) fixed nitrogen transformation and emission coefficients derived from the literature. Consequently, the model is intended to represent annual nitrogen flow patterns and relative loss pathways rather than short-term emission dynamics. These assumptions allow the model to provide a simplified representation of farm-scale nitrogen dynamics while maintaining limited data requirements.

2.1.1 Animal compartment

The Animal compartment was based on the approach developed by Caprarulo et al. (2026). Model outputs included fecal nitrogen (NexF), urinary nitrogen (NexU), and, for lactating cows, nitrogen exported through milk (NexM). Total nitrogen excretion in feces and urine (TN_{animal}) was calculated as:

$$TN_{animal} = NexF + NexU$$

2.1.2 Barn compartment

The type of resting area determines the characteristics of the excreta, distinguishing between solid manure and slurry. The mass of solid manure was calculated as the sum of feces, urine, and bedding materials, whereas slurry mass also included washing water originating from the milking operations. The proportion of slurry and solid manure produced and the associated nitrogen partitioning were calculated according to animal category and housing type, using the coefficients established under the implementation framework of the

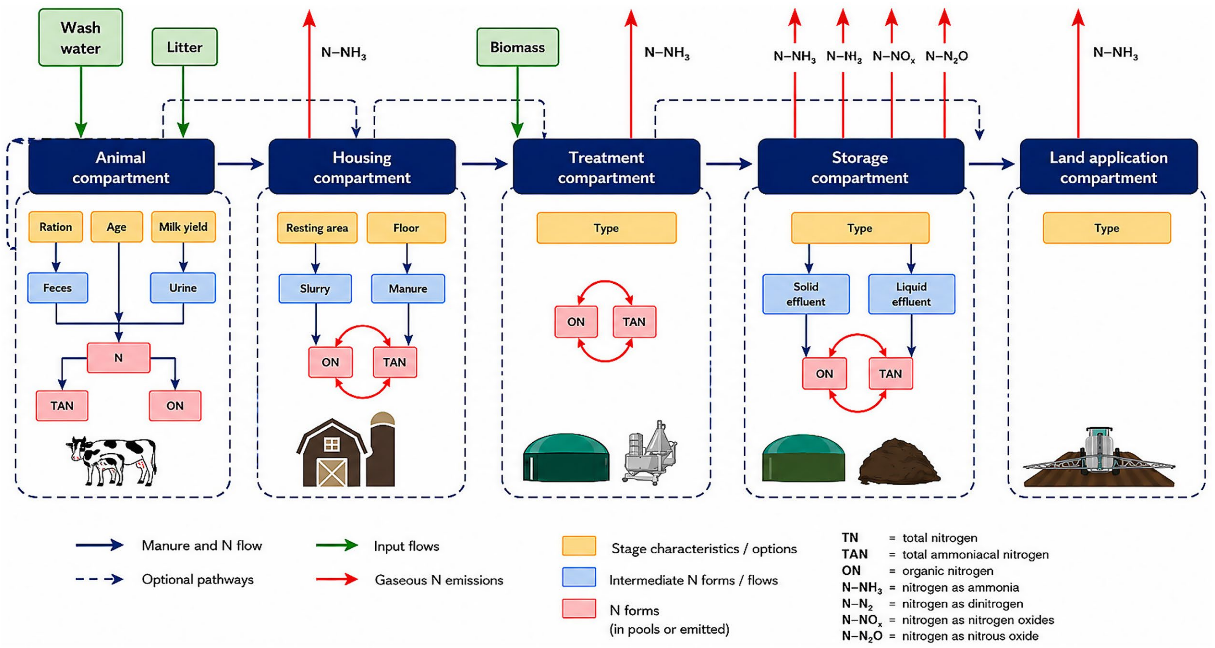

FIGURE 1
Schematic representation of the nitrogen flow model across the manure management chain. The model comprises five interconnected compartments (animal, housing, treatment, storage, and land application) through which manure and nitrogen are transferred. External inputs (wash water, litter, and biomass), management options, intermediate nitrogen forms, and gaseous nitrogen emissions are explicitly represented. Nitrogen transformations are simulated by tracking organic nitrogen (ON) and total ammoniacal nitrogen (TAN), whereas gaseous emissions include ammonia (N–NH_3), dinitrogen (N–N_2), nitrogen oxides (N–NO_x), and nitrous oxide (N–N_2O). Solid arrows indicate manure and nitrogen flows, dashed arrows represent optional pathways, green arrows indicate external inputs, and red arrows indicate gaseous nitrogen emissions.

TABLE 1 Allocation coefficients used to partition excreta into slurry and solid manure fractions according to animal category and housing system (Council of the European Communities, 1991).

Animal category	Housing system	Slurry fraction	Solid manure fraction
Adult dairy cows	Permanent litter	0.24	0.76
	Cubicles without bedding	1.00	0.00
	Tail-to-tail cubicles	0.51	0.49
	Head-to-head cubicles	0.33	0.67
	Full straw bedding	0.23	0.77
	Sloped litter	0.20	0.80
Replacement heifers	Resting area litter	0.32	0.68
	Cubicles without bedding	1.00	0.00
	Tail-to-tail cubicles	0.54	0.46
	Head-to-head cubicles	0.30	0.70
	Full straw bedding	0.10	0.90
	Sloped litter	0.10	0.90
	Slatted floor	1.00	0.00

Nitrates Directive (91/676/EEC) (Council of the European Communities, 1991) (Table 1).

$$TN_{manure} = TN_{animal} \times EF_{manure}$$

$$TN_{slurry} = TN_{animal} \times EF_{slurry}$$

Total ammoniacal nitrogen at barn level (TAN_{barn}) was estimated separately for the slurry and solid manure fractions, assuming 0.48 kg TAN /kg TN ($f_{TAN,slurry}$) and 0.16 kg TAN /kg TN ($f_{TAN,solid}$), respectively, according to de Vries et al. (2020). Organic nitrogen (ON_{barn}) was calculated as the difference between total nitrogen and TAN.

$$TAN_{slurry} = TN_{slurry} \times f_{TAN,slurry}$$

$$TAN_{manure} = TN_{manure} \times f_{TAN,manure}$$

$$ON_{slurry} = TN_{slurry} - TAN_{slurry}$$

$$ON_{manure} = TN_{manure} - TAN_{manure}$$

Barn NH_3 emissions ($N-NH_{3_{barn}}$) were estimated as a function of available TAN, floor type, and slurry removal frequency. A baseline emission factor (EF_{barn}) of 0.143 kg NH_3/kg TAN was applied and adjusted according to floor characteristics following de Vries et al. (2020). The TAN transferred to subsequent compartments was calculated by subtracting volatilized NH_3 from the available TAN pool.

$$N-NH_{3_{slurry}} = TAN_{slurry} \times EF_{barn}$$

$$N-NH_{3_{manure}} = TAN_{manure} \times EF_{barn}$$

$$TAN_{slurry,out} = TAN_{slurry} - N-NH_{3_{slurry}}$$

$$TN_{slurry,out} = TN_{slurry} - N-NH_{3_{slurry}}$$

$$TAN_{manure,out} = TAN_{manure} - N-NH_{3_{manure}}$$

$$TN_{manure,out} = TN_{manure} - N-NH_{3_{manure}}$$

2.1.3 Treatment compartment

The treatment compartment currently includes the three manure treatment types presently applied in the study area: (i) anaerobic digestion (AD), (ii) solid–liquid separation (SP) and (iii) anaerobic digestion combined with solid–liquid separation (AD+SP). Nevertheless, the compartmental structure of the model allows the integration of additional treatment technologies through the implementation of specific transformation and emission factors.

For anaerobic digestion systems, additional vegetal biomass inputs, characterized by their organic nitrogen ($ON_{biomass}$) and total ammoniacal nitrogen ($TAN_{biomass}$) contents, were considered. During the retention period, nitrogen mineralization was modeled as the conversion of a fraction of ON into TAN considering a fixed mineralization factor equal to 0.32 kg TAN/kg ON applied to the amount of ON in input (EEA, 2019b). Ammonia emissions during the anaerobic digestion were estimated using a fixed factor equal to 0.0009 kg N-NH_3/kg total nitrogen entering the digester (EEA, 2019b).

$$ON_{dig,in} = \left(ON_{manure} + ON_{slurry} + ON_{biomass}\right) \times 0.68$$

$$TAN_{dig,in} = TAN_{slurry,out} + TAN_{manure,out} + TAN_{biomass} + \left(ON_{slurry} + ON_{manure} + ON_{biomass}\right) \times 0.32$$

The total nitrogen entering the digester ($TN_{dig,in}$) was defined as the sum of organic nitrogen ($ON_{dig,in}$) and total ammoniacal nitrogen ($TAN_{dig,in}$).

$$TN_{dig,in} = TAN_{dig,in} + ON_{dig,in}.$$

$$N-NH_{3,dig} = TN_{dig,in} \times 0.0009.$$

The nitrogen remaining in the digestate after ammonia volatilization ($TN_{dig,out}$ and $TAN_{dig,out}$) represented the output of the anaerobic digestion module and constituted the input to the subsequent manure management stage, either storage or solid–liquid separation, depending on the treatment configuration.

$$TAN_{dig,out} = TAN_{dig,in} - N - NH_{3_{dig}}$$

$$TN_{dig,out} = TN_{dig,in} - N - NH_{3_{dig}}$$

The second treatment is solid–liquid separation. The process was modelled according to the separation efficiencies reported in the Nitrates Directive (CEE, 2020; Regione Lombardia, 2020), accounting for separator technology (i.e., its specific performance) and the DM content of the incoming effluent (low: DM < 4%; medium: DM = 4–8%; high: DM > 8%) (Table 2).

The separator received either slurry from the housing system or digestate from the anaerobic digestion process, depending on the treatment configuration. Accordingly, $TN_{sep,in}$ and $TAN_{sep,in}$ denote the total nitrogen and total ammoniacal nitrogen, respectively, of the effluent entering the separator, corresponding to either slurry or digestate depending on the treatment configuration. The distribution of TN between the liquid and solid fractions was calculated using separator-specific TN separation efficiencies ($EF_{sep,liq,TN,eff}$ and $EF_{sep,sol,TN,eff}$, respectively), applied to $TN_{sep,in}$.

The distribution of TAN was calculated independently using separator- and effluent-specific (slurry or digestate) TAN allocation factors ($EF_{sep,liq,TAN,eff}$ and $EF_{sep,sol,TAN,eff}$, respectively), applied to $TAN_{sep,in}$.

Ammonia emissions during solid–liquid separation were estimated using the technology-specific emission factor ($EF_{N-NH_3,sep}$). The nitrogen remaining after ammonia volatilization represented the input to the subsequent storage compartments.

$$N - NH_{3_{sep}} = TN_{sep,in} \times EF_{N-NH_{3,sep}}$$

$$TN_{sep,out} = TN_{sep,in} - N - NH_{3_{sep}}$$

$$TAN_{sep,out} = TAN_{sep,in} - N - NH_{3_{sep}}$$

$$ON_{sep,out} = TN_{sep,out} - TAN_{sep,out}$$

The nitrogen content of the liquid and solid fractions was estimated as:

$$TN_{liquid\ fraction} = TN_{sep,in} \times EF_{sep\_liq\_TN\_eff}$$

$$TAN_{liquid\ fraction} = TAN_{sep,in} \times EF_{sep\_liq\_TAN\_eff}$$

$$TN_{solid\ fraction} = TN_{sep,in} \times EF_{sep\_sol\_TN\_eff}$$

$$TAN_{solid\ fraction} = TAN_{sep,in} \times EF_{sep\_sol\_TAN\_eff}$$

2.1.4 Storage compartment

The storage compartment receives the organic nitrogen ($ON_{stor,in}$) and total ammoniacal nitrogen ($TAN_{stor,in}$) flows generated upstream in the effluent management chain. Depending on the management scenario, these flows may originate directly from the housing system (i.e., in the absence of treatment) or from the effluent produced after anaerobic digestion, solid–liquid separation, or anaerobic digestion followed by solid–liquid separation. During the storage period, both nitrogen mineralization and immobilization processes were considered (EEA, 2019a).

$$ON_{stor,pre} = ON_{stor,in} \times 0.90 + TAN_{stor,in} \times 0.25$$

$$TAN_{stor,pre} = ON_{stor,in} \times 0.10 + TAN_{stor,in} \times 0.75$$

Gaseous nitrogen losses during storage were quantified according to the type of storage system and the physical characteristics of the manure matrix (Table 3). Specifically, stackable effluent fractions were assigned to solid manure storage systems, whereas non-stackable fractions were assigned to slurry storage systems, with emission factors applied accordingly. Emissions included ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), and dinitrogen (N_2). Ammonia volatilization was first estimated based on the available total ammoniacal nitrogen (TAN) content, after which the emissions of N_2, NO, and N_2O were calculated from the remaining TAN following NH_3 volatilization (EEA, 2019a; IPCC, 2019).

$$N - NH_{3,stor} = TAN_{stor,pre} \times EF_{N-NH_3,stor}$$

$$N - N_{2stor} = \left(TAN_{stor,pre} - N - NH_{3,stor}\right) \times EF_{N-N_2,\ stor}$$

$$N - NO_{stor} = \left(TAN_{stor,pre} - N - NH_{3,stor}\right) \times EF_{N-NO,stor}$$

$$N - N_2O_{stor} = \left(TAN_{stor,pre} - N - NH_{3,stor}\right) \times EF_{N-N_2O,stor}$$

Nitrogen output from storage was calculated as:

$$TAN_{stor,out} = TAN_{stor,pre} - N - NH_{3,stor} - N - N_{2stor} - N - NO_{stor} - N - N_2O_{stor}$$

2.1.5 Land application

During land application, N-NH_3 emissions were calculated based on the type of effluent and the spreading technique employed starting from the TAN available in the effluent (EEA, 2019a; Giner Santonja et al., 2010) (Table 4).

$$N - NH_{3,field} = TAN_{stor,out} \times EF_{N-NH_3,field}$$

2.2 Dairy farm data collection

Ten commercial Holstein dairy farms located in the Po Valley (Lombardy region, Northern Italy) were selected to capture the variability of environmental and management conditions typical of the region. Farm selection criteria included herd size, housing system, and effluent management practices. All farms operated free-stall housing systems, although substantial variability was observed in barn design and herd management. The number of lactating cows per farm ranged from 35 to 601 animals (mean ± SD: 216.9 ± 200.9), with an average daily milk yield of 36.1 ± 3.6 kg cow^{-1} day^{-1}. Lactating cows accounted for approximately 39% of the total herd, while heifers represented 32%.

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TABLE 2 Separation efficiencies used in the solid–liquid separation module according to feedstock characteristics and separator technology [adapted from CEE (2020)].

Feedstock dry matter content	Feedstock type	Separator type	Liquid separated fraction	Solid separated fraction	TN liquid separated fraction	TN solid separated fraction	TAN liquid separated fraction	TAN solid separated fraction	EF N-NH_3 (kg/kg TN)
Low	Slurry	Screen separator	0.90	0.10	0.81	0.19	0.84	0.16	0.01
Low	Slurry	Counter-rotating rollers / screw press separator	0.96	0.04	0.94	0.06			
Low	Slurry	Centrifuge separator	0.86	0.14	0.76	0.24			
Medium	Slurry	Screen separator	0.83	0.17	0.61	0.39			
Medium	Slurry	Counter-rotating rollers / screw press separator	0.87	0.13	0.84	0.16			
Medium	Slurry	Centrifuge separator	0.82	0.19	0.70	0.30			
High	Slurry	Screen separator	0.82	0.18	0.50	0.50			0.02
High	Slurry	Counter-rotating rollers / screw press separator	0.74	0.26	0.73	0.27			
High	Slurry	Centrifuge separator			0.63	0.37			
Low	Digestate	Counter-rotating rollers / screw press separator	0.96	0.04	0.94	0.06	0.91	0.09	0.01
Low	Digestate	Centrifuge separator	0.86	0.14	0.76	0.24			
Medium	Digestate	Counter-rotating rollers / screw press separator	0.84	0.16	0.84	0.16			
Medium	Digestate	Centrifuge separator	0.82	0.19	0.70	0.30			
High	Digestate	Counter-rotating rollers / screw press separator	0.73	0.27	0.73	0.27			0.02
High	Digestate	Centrifuge separator	0.74	0.26	0.63	0.37			

TABLE 3 Nitrogen emission factors (EF) adopted for manure storage systems according to manure physical characteristics and storage management strategy (EEA, 2019a; IPCC, 2019).

Manure type	Storage system	EF N-NH_3 (kg/ kg TAN)	EF N-N_2O (kg/ kg TN)	EF N-NO (kg/ kg TAN)	EF N-N_2 (kg/ kg TAN)
Non stackable effluent	Open lagoon or uncovered tank	0.25	0.00	0.00	0.00
	Reduced surface-to-volume ratio (<0.2)	0.14	0.01	0.00	0.00
	Flexible cover (tent)	0.03	0.01	0.00	0.00
	Rigid cover	0.03	0.01	0.00	0.00
	Bag storage	0.00	0.01	0.00	0.00
	Floating flexible cover	0.10	0.01	0.00	0.00
	Natural crust	0.15	0.01	0.00	0.00
	Lightweight bulk material cover (e.g., LECA)	0.13	0.01	0.00	0.00
	Straw cover	0.15	0.01	0.00	0.00
	Floating geometric tiles	0.13	0.01	0.00	0.00
	Floating plastic spheres	0.13	0.01	0.00	0.00
	Reduced surface-to-volume ratio + flexible cover	0.01	0.01	0.00	0.00
	Reduced surface-to-volume ratio + floating cover	0.06	0.01	0.00	0.00
	Surface-to-volume ratio + rigid cover	0.01	0.01	0.00	0.00
	Treated slurry after nitrification–denitrification	0.01	0.01	0.00	0.00
Stackable effluent	Open heap	0.32	0.01	0.01	0.30
	Reduced surface-to-volume ratio	0.29	0.01	0.01	0.30
	Covered manure heap	0.19	0.01	0.01	0.30
	Barn storage	0.19	0.01	0.01	0.30
	Covered field storage	0.19	0.01	0.01	0.30
	Compost storage	0.03	0.01	0.01	0.30

TAN, total ammoniacal nitrogen; TN, total nitrogen.

TABLE 4 Ammonia emission factors adopted for manure field application systems (Giner Santonja et al., 2010).

Manure type	Application method	EF N-NH_3 (kg/kg TAN)
Non stackable effluent	Broadcast application without incorporation	0.69
	Fertigation	0.48
	Trailing hose (surface bands)	0.45
	Trailing shoe (bands with soil scarification)	0.35
	Shallow injection (open slots)	0.21
	Deep injection (closed slots)	0.07
	Shallow injection (closed slots)	0.14
	Trailing hose + incorporation within 12 h	0.22
	Trailing hose + incorporation within 24 h	0.36
	Trailing hose + incorporation within 4 h	0.20
	Trailing shoe + incorporation within 12 h	0.17
	Trailing shoe + incorporation within 24 h	0.28
	Trailing shoe + incorporation within 4 h	0.15
	Treated slurry application	0.07
	Low-pressure fertigation (drip hoses)	0.07
	Incorporation within 12 h	0.38
	Incorporation within 24 h (summer, T > 20°C)	0.55
	Incorporation within 24 h (spring/autumn, T < 20 °C)	0.48
	Incorporation within 4 h	0.24
	Immediate incorporation (non-inversion tillage)	0.21
Stackable effluent	Broadcast application without incorporation	0.46
	Compost or dried poultry manure application (>80% DM)	0.23
	Incorporation within 12 h	0.25
	Incorporation within 24 h	0.32
	Incorporation within 4 h	0.18
	Immediate incorporation (non-inversion tillage)	0.18

The model was applied individually to each farm. Farms were monitored over a 30-month period (June 2021–June 2023), with data collected twice per year to account for seasonal variability in management practices. Information collected included animal numbers (expressed as six-month average presence) and daily feed rations for all animal categories. For lactating cows, milk yield and composition (fat and protein content) were also recorded.

Housing characteristics included the type of resting area, bedding material and renewal frequency, flooring type in feeding areas, and manure removal systems. Information on effluent management included treatment technologies, storage systems and land application methods.

2.3 Preliminary model evaluation

To assess the consistency of simulated nitrogen partitioning across the main stages of the effluent management chain, samples were collected from barn floors, pre-storage tanks and storage facilities. Digestate samples were collected at all facilities, while liquid and solid separated fractions were additionally sampled where separation technologies were present. For barn-floor sampling, three subsamples were collected and combined into a representative sample. The selected matrices were intended to represent the main nitrogen transformation and transfer processes occurring throughout the effluent management chain.

All samples were stored in airtight polyethylene containers, refrigerated during transport, and subsequently analyzed for total nitrogen (TN), total ammoniacal nitrogen (TAN), dry matter (DM), and crude protein (CP). Dry matter content was determined by oven drying at 65 °C for 24 h according to Commission Regulation (EC) No. 152/2009, while crude protein content was determined using the Kjeldahl method (AOAC, 2001.11).

Model outputs were compared with measured total nitrogen concentrations in the sampled effluent matrices. The comparison was intended as a plausibility assessment of the simulated nitrogen partitioning among the different effluent fractions generated throughout the management chain and not as a full quantitative validation of emission estimates.

3 Results

3.1 Nitrogen partitioning and emissions in the barn compartment

Nitrogen flows in the Barn compartment are summarized in Table 5. Total ammoniacal nitrogen (TAN) accounted for 24.0 ± 2.0% of total nitrogen (TN), while nitrogen was partitioned almost equally between the slurry (51.5%) and manure (48.5%) fractions. On average, 2.75 ± 0.64% of nitrogen intake (NI) was lost as ammonia (NH_3) within the housing system.

The slurry fraction represented the main source of NH_3 emissions, accounting for 2.08 ± 0.91% of NI, whereas emissions from manure were substantially lower (0.67 ± 0.29% of NI). Despite the differences in manure management systems among farms, total NH_3 losses remained relatively consistent.

When farms were grouped according to the predominant excreta management system, NH_3 losses were higher in slurry based system instead manure-based farms (3.34 ± 0.07 and 2.16 ± 0.05 %NI, respectively).

3.2 Nitrogen losses during storage

Nitrogen losses occurring during storage are summarized in Tables 6, 7. Across the eight untreated farms, total nitrogen losses averaged 7.20 ± 6.43% of NI, corresponding to 12.97 ± 1.44% of the total nitrogen entering storage.

In slurry storage systems, ammonia nitrogen (N-NH_3) was the dominant gaseous nitrogen species, accounting for 91.6 ± 1.3% of total gaseous N losses. Emissions of N-N_2, N-N_2O, and N-NO_x were considerably lower, contributing 6.4 ± 1.0%, 1.9 ± 0.3%, and 0.06 ± 0.01% of total gaseous losses, respectively.

In solid manure storage systems, total nitrogen losses averaged 4.68 ± 6.88% of NI. In contrast to slurry storage, gaseous losses were more evenly distributed among nitrogen species. N-NH_3 represented 40.5 ± 1.8% of total losses, followed by N-N_2 (38.0 ± 1.7%), N-N_2O (20.2 ± 3.6%), and N-NO_x (1.3 ± 0.06%).

When farms were grouped according to the predominant effluent type, slurry-dominant farms showed slightly lower total nitrogen losses during storage (4.55 ± 0.59% of NI) than manure-dominant farms (9.85 ± 8.80% of NI). However, the contribution of ammonia to total gaseous losses was greater in slurry-based systems (78.4%) than in manure-based systems (75.9%).

3.3 Speciation of gaseous N losses

The relative contribution of the different gaseous nitrogen pathways is reported in Table 8. Ammonia nitrogen volatilization (N-NH_3) was the dominant loss pathway, accounting on average for 77.2 ± 8.5% of total gaseous N losses. The remaining losses occurred as N_2 (13.8 ± 6.5%), N-N_2O (8.6 ± 2.1%), and N-NO_x (0.46 ± 0.22%). Expressed as a proportion of nitrogen intake (NI), these pathways corresponded to 5.9% for N-NH_3, 1.1% for N-N_2, 0.7% for N-N_2O, and 0.04% for N-NO_x.

The composition of gaseous losses differed according to the predominant effluent management system. In slurry-dominant farms, N-NH_3 represented 84.8% of total gaseous losses, while N-N_2 and N-N_2O accounted for 7.8 and 7.2%, respectively. In contrast, manure-dominant farms showed a lower contribution of N-NH_3 (69.6%) and higher proportions of N-N_2 (19.7%) and N-N_2O (10.1%).

These results indicate that slurry-based systems primarily promote ammonia volatilization, whereas manure-based systems favor a more diversified distribution of gaseous nitrogen losses.

3.4 Treatment compartment: anaerobic digestion and solid–liquid separation

Nitrogen dynamics in the treatment systems are summarized in Table 9. Two treatment configurations were evaluated: anaerobic digestion alone (AD) and anaerobic digestion combined with solid–liquid separation (AD+SLS).

Nitrogen losses during treatment were limited in both configurations, corresponding to 1.62 and 0.09% of total digester N input in the AD+SLS and systems, respectively. Consequently, most of the nitrogen entering the treatment systems was retained in the resulting digestate fractions.

The composition of the incoming material differed between systems. In the AD+SLS configuration, slurry and manure accounted for 50.6 and 49.4% of the input, respectively, whereas the AD-only system received 49.40% slurry and 73.48% manure.

TABLE 5 Nitrogen partitioning and ammonia emissions in the housing (barn) compartment. Distribution of manure between slurry and solid manure, partitioning of nitrogen (N) into total ammoniacal nitrogen (TAN), and ammonia nitrogen (N–NH_3) emissions from slurry, manure, and the overall housing compartment.

Farm ID	Slurry	Manure	N slurry	TAN slurry	N manure	TAN manure	N-NH_3 slurry barn loss	N-NH_3 manure barn loss	N-NH_3 barn loss	N-NH_3 barn loss	N-NH_3 barn loss
	%	%	%	%	%	%	%N	%N	%NI	%N	%TAN
1	76.73	23.27	0.46	0.22	0.08	0.08	5.84	1.17	3.25	4.42	12.33
2	75.50	24.50	0.46	0.22	0.09	0.09	6.25	1.11	3.41	4.81	13.02
3	77.64	22.36	0.49	0.24	0.08	0.08	5.84	1.37	3.35	4.39	12.36
4	28.80	71.20	0.51	0.24	0.07	0.07	5.94	1.59	2.10	7.07	12.42
5	24.70	75.30	0.51	0.24	0.07	0.07	6.25	1.17	2.16	8.12	13.07
6	31.97	68.03	0.47	0.23	0.07	0.07	5.89	1.49	2.16	6.73	12.33
7	64.25	35.75	0.45	0.22	0.07	0.07	6.25	0.89	3.37	5.02	13.05
8	32.28	67.72	0.57	0.27	0.08	0.08	5.84	1.49	2.21	6.49	12.31
Mean	51.48	48.52	0.49	0.24	0.08	0.08	6.01	1.28	2.75	5.88	12.61
SD	24.03	24.03	0.04	0.02	0.01	0.01	0.20	0.24	0.64	1.40	0.36

Values are expressed as percentages of animal nitrogen intake (%NI), total excreted nitrogen (% N) or total ammoniacal nitrogen (% TAN), as indicated. Data are reported for each farm together with the mean and standard deviation (SD).
N, total nitrogen; TAN, total ammoniacal nitrogen; N–NH_3, nitrogen emitted as ammonia.

Digestate total nitrogen concentration was 0.46% in the AD-only system and 0.56% in the AD+SLS system. In the latter configuration, nitrogen was unevenly distributed between the separated fractions. The liquid digestate contained 0.47% total nitrogen (TN) and 0.20% total ammoniacal nitrogen (TAN), whereas the solid digestate contained 0.77% TN and 0.10% TAN. Overall, the solid fraction exhibited a higher total nitrogen concentration than the liquid fraction.

The composition of gaseous nitrogen losses also differed between treatment systems. In the AD+SLS configuration, N-NH_3 was the dominant gaseous form, accounting for 76.65 and 14.97% of gaseous losses from the liquid and solid fractions, respectively, while N-N_2 represented 14.03% of losses from the solid fraction. In the AD-only system, gaseous losses were considerably lower, with N-NH_3 and N-N_2 accounting for 7.37 and 0.15% of total losses, respectively.

3.5 Model evaluation

The comparison between simulated and measured nitrogen concentrations should be interpreted as a plausibility check aimed at assessing the internal consistency of nitrogen partitioning along the effluent management chain rather than as a full quantitative validation of emission estimates.

Simulated and measured total nitrogen (TN) concentrations (% fresh mass) were compared for the main effluent matrices generated throughout the manure management system (Table 10), including slurry at different management stages, stored manure, digestate, and separated digestate fractions.

The model generally reproduced the observed range of nitrogen concentrations across the different matrices. For slurry collected from lactating cow barns and pre-storage tanks, simulated N concentrations were higher than the measured values (0.49 ± 0.03% vs. 0.39% and 0.46 ± 0.03% vs. 0.30%, respectively). In contrast, the simulated concentration for stored slurry (0.25 ± 0.05%) closely matched the measured value (0.26%).

For solid manure, the model estimated a higher N concentration than that observed analytically (0.82 ± 0.20% vs. 0.53%). Digestate N concentration was also moderately overestimated (0.46% vs. 0.38%). The highest agreement between simulated and measured values was observed for the solid digestate fraction, for which nitrogen concentrations were nearly identical (0.77 and 0.76%, respectively). For the liquid digestate fraction, the model estimated a higher N concentration than that measured experimentally (0.47% vs. 0.32%).

Overall, the comparison indicated that the model was able to reproduce the main patterns of nitrogen partitioning among the different effluent fractions, although a tendency to overestimate nitrogen concentrations was observed in several matrices.

4 Discussion

The present study demonstrates that a simplified compartmental approach can effectively describe nitrogen flows and losses along the dairy effluent management chain while maintaining limited data requirements. Despite its relatively simple structure, the model was able to reproduce the main nitrogen partitioning patterns observed in intensive dairy systems and to identify the management stages responsible for the largest nitrogen losses.

4.1 Nitrogen losses and critical control points along the effluent management chain

Total nitrogen losses observed in the surveyed farms were consistent with values reported for European dairy production systems (Hou et al., 2017; Velthof et al., 2015). Across untreated farms, nitrogen losses averaged 9.2 ± 1.2% of excreted nitrogen, confirming that a

TABLE 6 Slurry nitrogen partitioning and gaseous nitrogen emissions during slurry storage. Nitrogen partitioning in slurry entering the storage compartment and total nitrogen losses during storage, expressed as percentages of total nitrogen (% N), total ammoniacal nitrogen (% TAN), and nitrogen input (% NI).

Farm ID	N slurry	TAN	Total N loss	Total N loss	Total N loss	N-NO	N-N_2	N-NH_3	N-N_2O
	%	%	% N	% TAN	%NI	% total N loss	% Total N loss	% Total N loss	% Total N loss
1	0.28	0.14	3.35	11.30	2.66	0.09	2.65	88.46	8.79
2	0.29	0.14	4.29	16.31	3.67	0.06	1.84	91.98	6.12
3	0.32	0.16	5.22	16.3	3.98	0.06	1.84	92.00	6.10
4	0.16	0.08	2.00	16.31	1.54	0.06	1.84	92.00	6.10
5	0.22	0.11	1.29	16.31	1.38	0.06	1.84	91.98	6.12
6	0.23	0.11	2.06	16.30	1.67	0.06	1.84	92.00	6.100
7	0.26	0.13	3.31	16.31	3.47	0.06	1.84	91.98	6.12
8	0.26	0.13	2.18	16.3	1.78	0.06	1.84	92.00	6.1
Mean	0.25	0.13	2.96	15.68	2.52	0.06	1.94	91.55	6.44
SD	0.05	0.03	1.32	1.77	1.06	0.01	0.29	1.25	0.95

The relative contribution of each gaseous nitrogen species to total nitrogen losses is also reported. Data are presented for each farm together with the mean and standard deviation (SD).
N, total nitrogen; TAN, total ammoniacal nitrogen; NI, nitrogen input to the storage compartment; N–NH_3, nitrogen emitted as ammonia; N–N_2, nitrogen emitted as dinitrogen; N–N_2O, nitrogen emitted as nitrous oxide; N–NO_x, nitrogen emitted as nitrogen oxides.

TABLE 7 Manure nitrogen partitioning and gaseous nitrogen emissions during solid manure storage.

Farm ID	Slurry			Manure			$N-NH_3$ slurry barn loss	$N-NH_3$ manure barn loss	$N-NH_3$ barn loss		
	%	TN%	TAN%	%	TN%	TAN%	%TN	%TN	%NI	%TN	%TAN
1	76.73	0.46	0.22	23.27	0.08	0.08	5.84	1.17	3.25	4.42	12.33
2	75.50	0.46	0.22	24.50	0.09	0.09	6.25	1.11	3.41	4.81	13.02
3	77.64	0.49	0.24	22.36	0.08	0.08	5.84	1.37	3.35	4.39	12.36
4	28.80	0.51	0.24	71.20	0.07	0.07	5.94	1.59	2.10	7.07	12.42
5	24.70	0.51	0.24	75.30	0.07	0.07	6.25	1.17	2.16	8.12	13.07
6	31.97	0.47	0.23	68.03	0.07	0.07	5.89	1.49	2.16	6.73	12.33
7	64.25	0.45	0.22	35.75	0.07	0.07	6.25	0.89	3.37	5.02	13.05
8	32.28	0.57	0.27	67.72	0.08	0.08	5.84	1.49	2.21	6.49	12.31
Mean	51.48	0.49	0.24	48.52	0.08	0.08	6.01	1.28	2.75	5.88	12.61
SD	24.03	0.04	0.02	24.03	0.01	0.01	0.20	0.24	0.64	1.40	0.36

Nitrogen partitioning in solid manure entering the storage compartment and total nitrogen losses during storage, expressed as kilograms (kg), percentages of total nitrogen (% N), total ammoniacal nitrogen (% TAN), and nitrogen input (% NI). The relative contribution of each gaseous nitrogen species to total nitrogen losses is also reported. Data are presented for each farm together with the mean and standard deviation (SD).
N, total nitrogen; TAN, total ammoniacal nitrogen; NI, nitrogen input to the storage compartment; $N–NH_3$, nitrogen emitted as ammonia; $N–N_2$, nitrogen emitted as dinitrogen; $N–N_2O$, nitrogen emitted as nitrous oxide; $N–NO_x$, nitrogen emitted as nitrogen oxides.

TABLE 8 Summary of nitrogen losses across the manure management chain.

Farm ID	Total N loss	Total N loss	N loss slurry	N loss manure	N loss barn	N loss storage	N-NO	$N-N_2$	$N-NH_3$	$N-N_2O$
	% NI	% Nex	% N loss	% N loss	% Total N loss	% Total N loss	% Total N loss	% Total N loss	% Total N loss	% Total N loss
1	4.22	5.17	77.03	22.97	45.00	55.00	0.26	7.69	84.76	7.30
2	5.44	6.62	76.05	23.95	38.92	61.08	0.26	7.89	85.03	6.81
3	4.27	5.59	81.91	18.09	39.27	60.73	0.21	6.22	87.88	5.70
4	7.31	7.41	37.97	62.03	29.11	70.89	0.67	20.23	69.99	9.11
5	1.99	2.05	32.63	67.37	28.21	71.79	0.68	20.51	66.26	12.55
6	22.47	21.89	40.07	59.93	29.36	70.64	0.65	19.45	70.56	9.33
7	4.27	4.29	69.48	30.52	37.09	62.91	0.31	9.35	81.49	8.85
8	7.60	10.76	42.08	57.92	29.81	70.19	0.63	18.76	71.40	9.22
Mean	7.20	7.97	57.15	42.85	34.59	65.41	0.46	13.76	77.17	8.61
SD	6.43	6.16	20.72	20.72	6.28	6.28	0.22	6.46	8.45	2.08

Overall nitrogen losses for each farm, expressed as percentages of nitrogen input (% NI) and nitrogen excretion (% Nex). The contribution of slurry, manure, housing, and storage compartments to total nitrogen losses, as well as the relative contribution of each gaseous nitrogen species, is reported. Data are presented for each farm together with the mean and standard deviation (SD).
NI, nitrogen input; Nex, nitrogen excretion; $N–NH_3$, nitrogen emitted as ammonia; $N–N_2$, nitrogen emitted as dinitrogen; $N–N_2O$, nitrogen emitted as nitrous oxide; $N–NO_x$, nitrogen emitted as nitrogen oxides.

substantial proportion of dietary nitrogen remains vulnerable to environmental losses after excretion. These results highlight the importance of identifying critical control points within the manure management chain and support the need for integrated approaches capable of evaluating nitrogen transformations across the entire farm system (Castillo et al., 2000; Hristov et al., 2019; Velthof et al., 2015).

The model identified storage as the principal source of gaseous nitrogen losses, accounting for approximately two-thirds of total farm-scale emissions, whereas housing contributed the remaining one-third. Ammonia volatilization represented the dominant loss pathway throughout the system, while N_2 and N_2O contributed to a lesser extent. This distribution is consistent with previous studies describing storage as one of the most critical stages for nitrogen conservation in livestock systems (Oenema et al., 2007; Reidy et al., 2008).

4.2 Influence of effluent management pathways on nitrogen emissions

The model successfully differentiated between slurry-based and manure-based management systems, reproducing emission patterns widely reported in the literature. Slurry systems were characterized by greater ammonia volatilization, whereas manure-based systems

TABLE 9 Nitrogen partitioning and gaseous nitrogen losses in manure treatment systems.

System		AD+SLS	AD
Manure	%	49.40	73.48
	%TN	1.04	0.66
	%TAN	0.27	0.08
Slurry	%	50.60	26.52
	%TN	0.50	0.52
	%TAN	0.24	0.25
Barn emissions	NH_3-N (% NI)	9.60	7.70
	NH_3-N (% TAN)	13.00	13.00
Vegetable Biomass entering	%TN	1.13	1.20
	%TAN	0.00	0.00
Total mass entering the digester	%TN	0.91	0.59
	%TAN	0.21	0.10
Digestate	%TN	0.56	0.46
	%TAN	0.17	0.20
Liquid fraction	%TN	0.47	–
	%TAN	0.20	–
Solid fraction	%TN	0.77	–
	%TAN	0.10	–
Gaseous N losses (% of total N storage loss)	NH_3-N	85.59	91.86
	N_2-N	8.25	1.84
	N_2O-N	2.94	6.24
	NO_x-N	3.22	0.06

Nitrogen partitioning between slurry, manure, digestate, liquid fraction, and solid fraction, together with ammonia emissions from the housing compartment and gaseous nitrogen losses associated with the treatment systems. Nitrogen fractions are expressed as percentages of total nitrogen (TN), total ammoniacal nitrogen (TAN), animal nitrogen input (NI), or gaseous nitrogen losses, as indicated.
TN, total nitrogen; TAN, total ammoniacal nitrogen; NI, nitrogen input; AD, anaerobic digestion; AD+SLS, anaerobic digestion coupled with solid–liquid separation; NH_3–N, nitrogen emitted as ammonia; N_2–N, nitrogen emitted as dinitrogen; N_2O–N, nitrogen emitted as nitrous oxide; NO_x–N, nitrogen emitted as nitrogen oxides.

TABLE 10 Comparison between measured and modeled total nitrogen concentrations in manure and treatment products.

Item	Analysis		Model	
	Dry matter (%)	N (% fresh mass)	N (% fresh mass)	
Slurry (lactating cow. Barn floor)	14.99	0.39	0.49	±0.03
Slurry (tank pre storage)	9.46	0.30	0.46	±0.03
Slurry (storage)	7.78	0.26	0.25	±0.05
Manure (storage)	28.65	0.53	0.82	±0.20
Digestate (storage)	9.28	0.38	0.46	±0.00
Digestate-solid fraction (storage)	44.48	0.76	0.77	±0.00
Digestate-liquid fraction (storage)	7.17	0.32	0.47	±0.00

Measured and modeled total nitrogen (TN) concentrations expressed on a fresh mass basis (% fresh mass) for slurry, manure, digestate, and digestate fractions at different stages of the manure management chain. Measured values were obtained by laboratory analysis, whereas modeled values represent the mean ± standard deviation (SD) across the eight farms included in the study.
TN, total nitrogen; SD, standard deviation.

showed a larger contribution of N_2 and N_2O losses (Hristov et al., 2011; Montes et al., 2009; S. Petersen et al., 2007). These differences reflect the contrasting physical and biochemical conditions associated with liquid and solid manure management.

In slurry systems, the larger gas–liquid interface and the availability of ammoniacal nitrogen promote ammonia volatilization (Amon et al., 2006; Chadwick et al., 2011; Montes et al., 2009). Conversely, solid manure storage creates heterogeneous aerobic and anaerobic microenvironments that favor coupled nitrification–denitrification processes and therefore increase the relative importance of N_2 and N_2O emissions (Chadwick et al., 2011; Petersen et al., 2013). The ability of the model to reproduce these distinct pathways supports its capacity to confirms correct implementation of literature-derived emission factors.

4.3 Treatment technologies and nitrogen redistribution

The treatment module further demonstrated the flexibility of the modelling framework. Anaerobic digestion and anaerobic digestion combined with solid–liquid separation modified nitrogen distribution within the system while generating only limited gaseous losses during treatment. Most nitrogen remained within the digestate fractions, indicating that treatment technologies primarily influence nitrogen redistribution rather than nitrogen removal (Amon et al., 2006; Clemens et al., 2006).

The AD+SLS configuration resulted in a differentiated allocation of nitrogen between liquid and solid digestate fractions, creating opportunities for targeted nutrient management strategies. This aspect is particularly relevant in regions affected by nutrient surpluses, where the redistribution of nitrogen among different fractions can facilitate transport, storage, and field application planning. The modular structure of the model also allows the future inclusion of additional treatment technologies through the implementation of technology-specific transformation and emission coefficients.

4.4 Model evaluation and limitations

The comparison between simulated and measured nitrogen concentrations provided preliminary support for the model's ability to reproduce the main patterns of nitrogen partitioning along the effluent management chain. Agreement between modeled and measured values was particularly evident for stored slurry and solid digestate, whereas a tendency to overestimate nitrogen concentrations was observed in several liquid matrices.

These discrepancies are likely related to the simplifying assumptions adopted by the model, including steady-state conditions and homogeneous mixing within each compartment. Such assumptions do not fully capture temporal variability, dilution processes associated with wash water, or the heterogeneity typical of solid manure storage systems. Consequently, the model should not be interpreted as a tool for precise prediction of short-term emissions, but rather as a framework for representing average nitrogen flows and identifying the dominant pathways of nitrogen transformation and loss.

The present evaluation was also constrained by the limited availability of measured data for some treatment systems, particularly digestate and separated fractions. Additional datasets collected under different environmental and management conditions would allow a more comprehensive assessment of model performance and support further refinement of model coefficients.

4.5 Practical applications and future perspectives

One of the main strengths of the proposed framework lies in its balance between simplicity and resolution. Unlike inventory approaches based exclusively on generic emission factors, the model generates farm-specific estimates while requiring information that is generally available through routine farm records and advisory services. This characteristic makes the framework directly applicable in practical decision-support contexts.

At farm level, the model can support farmers and technical advisors in identifying critical nitrogen loss pathways and evaluating alternative management strategies. At territorial scale, the same framework can support producer organizations, advisory services, and policymakers in assessing the environmental performance of livestock systems and exploring the potential effects of mitigation measures. The compartmental structure also facilitates scenario analysis, enabling the evaluation of alternative housing systems, treatment technologies, storage configurations, and land application practices.

From a policy perspective, the proposed model may contribute to the implementation of nutrient management strategies promoted by the EU Nitrates Directive and the Farm to Fork Strategy by providing transparent and farm-specific estimates of nitrogen flows (EC, 2019). Future research should focus on validating the proposed framework across a larger number of farms and under different management conditions, as well as on the development of a more mechanistic and dynamic model capable of representing the temporal and seasonal dynamics of nitrogen transformations and emissions. The integration of such a model with sensor-based monitoring systems and digital farm platforms could ultimately provide dynamic decision-support tools for operational management and environmental reporting. In the long term, the proposed model may represents a step toward more data-driven, adaptive, and circular nitrogen management in dairy production systems.

5 Conclusion

This study presents a simplified compartmental model for quantifying nitrogen flows and losses along the main stages of manure management in intensive dairy farms. By combining process-based relationships with a limited set of farm-specific input data, the model provides a practical approach for estimating nitrogen partitioning and gaseous emissions across housing, manure treatment, storage, and land application.

Application of the model to commercial Holstein dairy farms in the Po Valley confirmed the major contribution of housing and storage to overall nitrogen losses and demonstrated the influence of manure management pathways on the distribution of nitrogen emissions. Despite its simplified structure, the framework was able to reproduce the main patterns of nitrogen partitioning observed in the analysed effluent matrices, supporting its use for identifying critical stages of the manure management chain and evaluating nitrogen flows at farm scale.

Overall, the proposed framework provides a transparent and operational methodology for improving the understanding of nitrogen dynamics in dairy production systems while maintaining limited data requirements. Although further validation under a broader range of farming conditions and the inclusion of additional treatment technologies and dynamic process representations would strengthen its applicability, the model offers a robust foundation for future developments aimed at supporting more efficient and environmentally sustainable manure management.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

GF: Conceptualization, Writing – review & editing, Writing – original draft, Formal analysis, Methodology, Data curation. AS: Formal analysis, Conceptualization, Writing – review & editing, Data curation. VC: Writing – review & editing, Investigation. ES: Writing – review & editing, Investigation. GG: Writing – review & editing, Supervision, Project administration.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. The graphical illustration included in this manuscript was generated with the assistance of ChatGPT (GPT-5.5, OpenAI; https://chatgpt.com) based on author-provided instructions and subsequently reviewed and edited by the authors. The authors take full responsibility for the content and accuracy of the final figure.

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