atmosphere

MDPI

Article

Formation of Secondary Inorganic $PM_{2.5}$ as Impacted by Ammonia Concentrations near an Animal Feeding Operation

Blake Stratton [1], Lingjuan Wang-Li [1,*], Wei Shi [2], Sanjay Shah [1], John Classen [1] and Kenneth Anderson [3]

[1] Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC 27695, USA; bestratt@ncsu.edu (B.S.); sbshah3@ncsu.edu (S.S.); classen@ncsu.edu (J.C.)
[2] Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC 27620, USA; wshi3@ncsu.edu
[3] Prestage Department of Poultry Science, North Carolina State University, Raleigh, NC 27608, USA; ken_anderson@ncsu.edu
* Correspondence: lwang5@ncsu.edu

Abstract

The impact of ammonia (NH_3) emissions from animal agriculture on the secondary formation of inorganic fine particulate matter (i.e., $iPM_{2.5}$) has become of great public concern. The formation of $iPM_{2.5}$ from NH_3 is known as the gas–particle partitioning of gaseous NH_3 and aerosol ammonium (NH_4^+), which is assumed to be in a thermodynamic equilibrium. This research aimed to gain an in-depth understanding of the impact of ambient NH_3 on secondary $iPM_{2.5}$ by analyzing the $PM_{2.5}$ mass closure, atmospheric chemical conditions, and the gas particle partitioning of NH_3-NH_4^+ in the near field of a poultry production unit in North Carolina. Samples of precursor gases (i.e., NH_3, SO_2, NO_2) to $iPM_{2.5}$ and $PM_{2.5}$ were taken on this poultry production unit at four sampling stations in four wind directions through summer, autumn and winter seasons to determine gas concentrations and $PM_{2.5}$ chemical compositions. It was discovered that this rural site contained low ambient concentrations of $iPM_{2.5}$ precursor gases, and $PM_{2.5}$ composition was dominated by organic carbon (OC) (80% to 94%) while $iPM_{2.5}$ fraction was insignificant (0% to 2%). Low availability of H_2SO_4 and HNO_3 gases (from SO_2 and NO_2 conversions) limited NH_3 neutralization potential and $iPM_{2.5}$ formation; moreover, high OC fraction may inhibit NH_4^+ formation. With the field measurements of ambient temperature, humidity, precursor gases and $PM_{2.5}$ chemical speciation data, the ISORROPIA-II thermodynamic equilibrium model was used to conduct the sensitivity analysis, and we found that $iPM_{2.5}$ was the most sensitive to increasing total HNO_3 (gas + aerosol) at low temperatures. The formation potential of $iPM_{2.5}$ at this rural site was at its highest during the wintertime when SO_2 was extremely low.

Keywords: ammonia; inorganic $PM_{2.5}$; precursor gas; thermodynamic equilibrium modeling

Check for updates

Academic Editor: Manish Shrivastava

Received: 31 December 2025
Revised: 26 January 2026
Accepted: 9 February 2026
Published: 11 February 2026

1. Introduction

Ammonia (NH_3) is a key component of the global nitrogen cycle and a dominant alkaline precursor in the atmosphere [1]. In the United States, agriculture is the largest source of NH_3 emissions, primarily from livestock and poultry production and fertilizer application [2–7]. Once emitted, NH_3 contributes to a range of environmental and public-health concerns through deposition to terrestrial and aquatic ecosystems [8–10] and through its role in the secondary formation of fine particulate matter ($PM_{2.5}$) [11–18]. Secondary inorganic $PM_{2.5}$ ($iPM_{2.5}$), composed mainly of ammonium sulfate and ammonium nitrate,

https://doi.org/10.3390/atmos17020188

is associated with adverse cardiovascular and respiratory outcomes [19–21] and reduced atmospheric visibility, making it a regulated air pollutant of significant concern.

The formation of $iPM_{2.5}$ is governed by gas–particle partitioning between gaseous NH_3 and acidic species such as sulfuric and nitric acids [22]. This partitioning is commonly assumed to occur under thermodynamic equilibrium and is strongly influenced by the relative availability of precursor gases (NH_3, SO_2, and NO_x), meteorological conditions, and aerosol chemical composition [22–25]. In regions with abundant SO_2 and NO_x emissions, reductions in NH_3 have been shown to be an effective strategy for lowering $iPM_{2.5}$ concentrations [12,15]. However, the relevance of this paradigm to rural agricultural environments, where NH_3 concentrations may be high but acidic precursor gases are limited, remains uncertain [13,14,16].

Animal feeding operations (AFOs), particularly poultry facilities, represent localized NH_3 "hotspots" in predominantly rural settings [4,7]. While NH_3 emissions from AFOs are well documented [1,4], their downwind impacts on $iPM_{2.5}$ formation are less well understood. High NH_3 availability alone does not guarantee substantial $iPM_{2.5}$ production; rather, the formation potential depends on atmospheric chemical conditions, including the balance between total ammonia, sulfate, and nitrate, as well as temperature and relative humidity [11,14]. Emerging evidence suggests that in NH_3-rich but acid-limited environments, secondary $iPM_{2.5}$ formation may be constrained, and organic aerosol fractions may further inhibit ammonium formation [26–28]. These interactions introduce uncertainty into assessments of agricultural NH_3 contributions to regional $PM_{2.5}$ burdens.

Thermodynamic equilibrium models, such as ISORROPIA-II, are widely used to evaluate gas–particle partitioning and predict inorganic aerosol composition under varying atmospheric conditions [27]. Although these models have been extensively applied in urban and regional studies, fewer investigations have combined detailed field measurements with thermodynamic modeling in the near-field of AFOs [16–18]. Moreover, model performance and inferred sensitivities may differ substantially in rural settings characterized by low SO_2 and NO_x concentrations and seasonally varying meteorology [13,16,28,29].

To address the aforementioned knowledge gaps, this study investigates the formation potential of secondary $iPM_{2.5}$ in the vicinity of a poultry production facility in North Carolina. Using multi-season field measurements of $PM_{2.5}$ chemical composition, precursor gases (NH_3, SO_2, and NO_2), and meteorological conditions, this work evaluates atmospheric chemical conditions relevant to NH_3 neutralization and $iPM_{2.5}$ formation. Thermodynamic equilibrium modeling with ISORROPIA-II is further employed to assess the sensitivity of $iPM_{2.5}$ formation to changes in precursor availability and environmental condition.

The overarching objective of this research is to improve understanding of how elevated ambient NH_3 concentrations from AFOs influence secondary inorganic $PM_{2.5}$ formation under rural, acid-limited conditions. Specifically, the study aims to (i) characterize spatial and seasonal variations in precursor gases and $PM_{2.5}$ composition near a poultry facility, (ii) assess atmospheric chemical conditions governing NH_3 neutralization potential, and (iii) evaluate the sensitivity of $iPM_{2.5}$ formation to NH_3 and nitrate availability using thermodynamic modeling. The findings provide science-based insights into the role of agricultural NH_3 emissions in $PM_{2.5}$ formation and inform air-quality management strategies in rural environments influenced by intensive animal production.

2. Materials and Methods

2.1. Research Site and Air Sampling Methods

This study was conducted at the Poultry Unit of the North Carolina Department of Agriculture (NCDA) Piedmont Research Station in Salisbury, North Carolina, a rural agricultural setting representative of animal feeding operations (AFOs) in the southeastern

United States. The facility consists of multiple mechanically ventilated poultry houses, a free-range pasture, and a manure storage area (Figure 1), all of which serve as potential sources of ammonia (NH_3) emissions. Surrounding land use is dominated by row crops managed under a no-till system, with no nearby major industrial emission sources. During the study period, poultry houses and manure storage were the primary NH_3 emission sources, while contributions of acidic precursor gases were expected to be low due to the rural location.

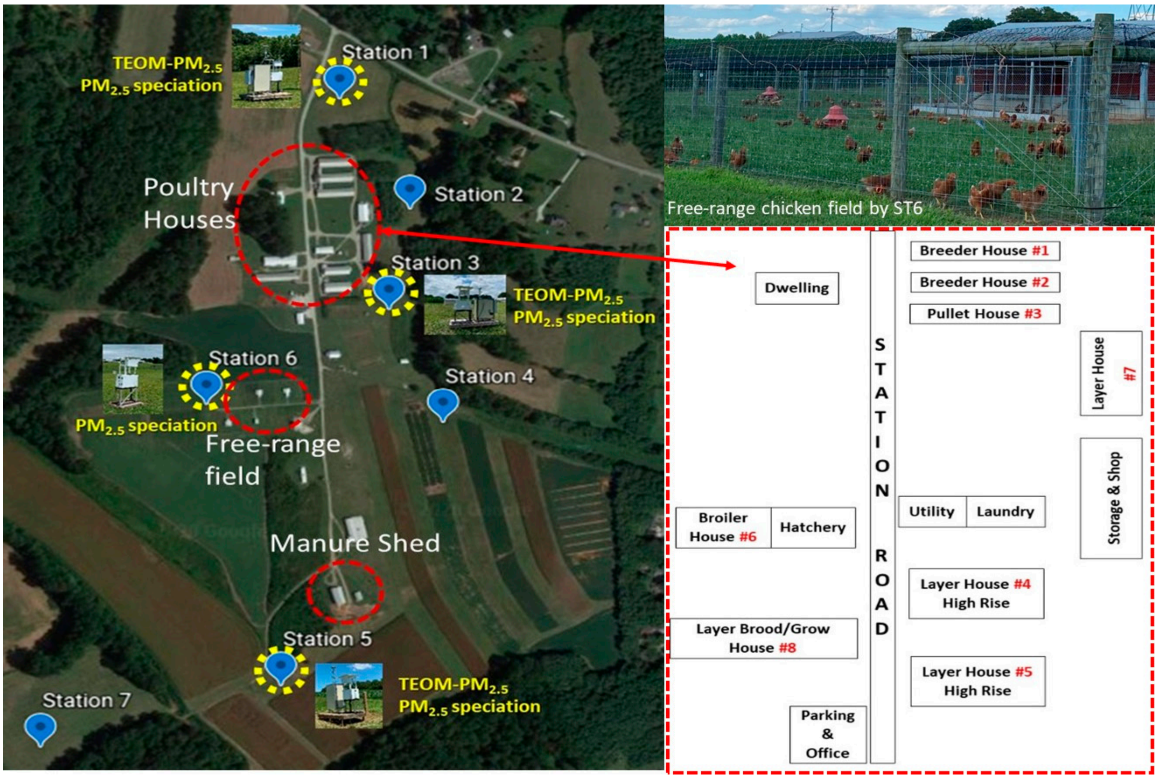

Figure 1. Research site layout and ambient air sampling locations.

Ambient air monitoring was conducted at four fixed sampling stations strategically positioned around the poultry facility to capture upwind and downwind conditions under varying wind directions (Stations 1, 3, 5 and 6 in Figure 1). The station layout ensured that at least one site was downwind of emission sources at any given time. All four stations were equipped with collocated $PM_{2.5}$ chemical speciation samplers and passive gas samplers to support $PM_{2.5}$ chemical speciation and gas sampling only.

Fine PM ($PM_{2.5}$) chemical composition was measured using Partisol Model 2300 chemical speciation samplers (Thermo Fisher Scientific, Franklin, MA, USA) operated on a 24 h sampling cycle (Figure 2). The samplers employed multiple parallel channels to collect $PM_{2.5}$ mass, inorganic ions, elemental species, and carbon fractions. Teflon filters were used for $PM_{2.5}$ mass and elemental analysis, nylon filters for ionic species (including NH_4^+, NO_3^-, and SO_4^{-2}), and quartz filters for organic and elemental carbon. To prevent positive sampling artifacts, honeycomb denuders coated with citric acid were installed upstream of nylon filters to remove gaseous NH_3 prior to particle collection.

Precursor gases (NH_3, SO_2, and NO_2) were measured using Ogawa passive samplers (Ogawa & Co., USA Inc., Pompano Beach, FL, USA) co-located at each monitoring station (Figure 2). At each sampling event, passive samplers were deployed for multi-day periods (6–14 days) to achieve sufficient sensitivity under low ambient concentrations typical of rural environments. Gas-phase NH_3 measured by passive samplers was used for concentration assessment.

Figure 2. Illustration of $PM_{2.5}$ speciation samplers (**left**), co-located samplers (**middle**), Ogawa passive samplers with replicates (**right**).

Sampling was conducted from July to December 2022, covering summer (July–August, $n = 10$), autumn (October, $n = 3$), and winter (November–December, $n = 7$) seasons to capture a wide range of meteorological and atmospheric chemical conditions. All samples were prepared, handled, and stored following established protocols to minimize contamination and ensure data quality. $PM_{2.5}$ filters and gas samples were subsequently analyzed for chemical composition and precursor gas concentrations using standardized laboratory methods. More details were reported by Stratton [30].

2.2. Meterological Data Collection

Meteorological data were obtained from a nearby automated weather station located approximately 1.6 km from the research site [31]. Hourly measurements of ambient temperature, relative humidity (RH), wind speed, and wind direction were retrieved for the duration of each $PM_{2.5}$ sampling event. For consistency with 24 h integrated air sampling, meteorological variables were averaged over the corresponding sampling periods.

The study period spanned summer, autumn, and winter seasons, encompassing a broad range of atmospheric conditions relevant to gas–particle partitioning and secondary inorganic $PM_{2.5}$ formation. Prevailing wind direction varied by season, influencing the relative upwind and downwind positioning of monitoring stations. Mean wind speeds during sampling events ranged from approximately 0.5 to 1.7 m s^{-1}, reflecting generally low-wind conditions typical of the rural study area.

Meteorological parameters were used to interpret spatial and temporal variability in precursor gas concentrations, $PM_{2.5}$ composition, and atmospheric chemical conditions, and served as key inputs for thermodynamic equilibrium modeling of inorganic aerosol formation.

2.3. Chemical Analyses and Concentration Determination

Chemical analyses of $PM_{2.5}$ chemical speciation samples included gravimetric mass, inorganic ions, elemental species, and carbon fractions. $PM_{2.5}$ mass and elemental composition were determined from Teflon filters. Filters were conditioned under controlled temperature and RH conditions prior to pre- and post-sampling weighing using a microbalance with a sensitivity of ±1 μg [32]. Elemental concentrations were quantified by energy-dispersive X-ray fluorescence (EDXRF) spectrometry, following standard protocols used by the U.S. EPA $PM_{2.5}$ Chemical Speciation Network [33]. $PM_{2.5}$ mass concentrations and elemental concentrations were determined by Equations (1) and (2), respectively:

$$C_{PM2.5} = \frac{m_2 - m_1}{Q \times t} \tag{1}$$

where $C_{PM2.5}$ is the ambient $PM_{2.5}$ mass concentration (µg m^{-3}); m_1 and m_2 are the pre-sampling and post-sampling filter masses (µg), respectively; Q is the volumetric sampling flow rate (16.7 $Lmin^{-1}$ = 0.96 m^3h^{-1}); and t is the sampling duration (h).

$$C_e = \frac{m_e}{Q_T \times t} \tag{2}$$

where C_e is the mass concentration of individual elements (μgm^{-3}); m_e is mass of individual elements on the filter (µg); Q_T is the air sampling flow rate through Teflon filter cartridge (16.7 $Lmin^{-1}$ = 0.96 m^3 h^{-1}); t is the sampling duration (24 h) of each sampling event.

Inorganic ionic species (NH_4^+, NO_3^-, SO_4^{-2}, Cl^-, Na^+, and K^+) were measured from nylon filters. Filters were extracted in deionized water using ultrasonic agitation, and the extracts were analyzed by ion chromatography (IC) [33]. The measured aqueous concentrations were converted to ambient air concentrations using the known extraction volume, sampling flow rate, and sampling duration (Equations (3) and (4)). Gas-phase ammonia collected by citric-acid-coated honeycomb denuders was similarly extracted in deionized water and analyzed by IC to determine NH_3 concentrations in air.

$$m_i = C_l \times V \tag{3}$$

$$C_i = \frac{m_i}{Q_N \times t} \tag{4}$$

where m_i is the mass of individual ionic species (NH_4^+, Na^+, and K^+, NO_3^-, SO_4^{-2}, Cl^-) (µg), C_l mass concentration (μgm^{-3}) of ionic species in DI water measured by IC; V is the volume (m^3) of DI water in extraction vials; C_i is the concentrations of individual ionic species (NH_4^+, Na^+, and K^+, NO_3^-, SO_4^{-2}, Cl^-) ($\mu g/m^{-3}$); Q_N is the air sampling flow rate through nylon filter cartridge (10 $Lmin^{-1}$ = 0.6 m^3 h^{-1}); t is the sampling duration (24 h) of each sampling event.

Organic carbon (OC) and elemental carbon (EC) were quantified from quartz filters using a thermal–optical aerosol analyzer (Sunset Laboratory Inc., Tigard, OR, USA) following the U.S. EPA $PM_{2.5}$ Chemical Speciation Network protocol [33]. Subsamples were analyzed, and reported area-based carbon loadings were converted to ambient concentrations using the effective filter collection area and total sampled air volume (Equations (5) and (6)).

$$m = D \times A \tag{5}$$

$$C_c = \frac{m}{Q_q \times t} \tag{6}$$

where m is the OC or EC mass loading (µg); D is the sample area density on the filter punch, i.e., the sub-sample (μgcm^{-2}); A is the area of the quartz filter (17.35 cm^2); C_c is the mass concentration of OC or EC (μgm^{-3}); Q_q is the air sampling flow rate through quartz filter cartridge (16.7 $Lmin^{-1}$ = 0.96 m^3 h^{-1}); t is the sampling duration (24 h) of each sampling event.

Precursor gases (NH_3, SO_2, and NO_2) collected by Ogawa passive samplers were analyzed by IC after aqueous extraction of the collection pads. Measured mass loadings were converted to time-averaged ambient gas concentrations based on sampler-specific diffusion coefficients, exposure duration, and effective sampling geometry (Equations (7) and (8)).

Field blanks were processed alongside samples, and blank-corrected values were used for all reported concentrations.

$$C_p\ (ppb) = \alpha_g \times \frac{m_g}{t} \tag{7}$$

$$C_p\left(\mu g m^{-3}\right) = \frac{P}{R * T} \times ppm \times MW \times 10^3 \tag{8}$$

where C_p is the concentrations of the precursor gases (NH_3, NO_2, SO_2) (ppb); α_g is a gas-specific ppb concentration conversion coefficient (ppb–min/ng) for by RTI International for Ogawa passive samplers, Its value depends on the target gas (NH_3, NO_2, or SO_2) and accounts for sampler geometry and diffusion characteristics; m_g is the mass loading on the pad (ng); t is passive sampling time (min); P is the atmospheric pressure (1 atm); R is the universal gas constant (0.082 L atm mol^{-1} K^{-1}); T the average temperature of the sampling event (K); MW is the molecular weight of the gas of interest, and ppm is the volume concentration of the precursor gas of interest (1 ppm = 1000 ppb).

Ambient $PM_{2.5}$ chemical species concentrations and precursor gas concentrations derived from these analyses were subsequently used to evaluate atmospheric chemical conditions, $PM_{2.5}$ mass closure, and gas–particle partitioning behavior. These concentration data also served as inputs for thermodynamic equilibrium modeling to assess the sensitivity of secondary inorganic $PM_{2.5}$ formation to precursor availability and meteorological conditions.

2.4. Atmospheric Chemical Conditions and $PM_{2.5}$ Mass Closure Analysis

Atmospheric chemical conditions governing secondary $iPM_{2.5}$ formation were evaluated using a set of established molar ratios and indicators that describe NH_3 neutralization potential and aerosol acidity (Equations (9)–(14)) [22]. These metrics were calculated from measured concentrations of precursor gases and $PM_{2.5}$ inorganic ions, including total ammonia ($NH_3 + NH_4^+$), total sulfate, and total nitrate. Collectively, the indicators characterize whether ambient conditions were NH_3-limited or acid-limited and assess the sensitivity of $iPM_{2.5}$ formation to changes in precursor availability. Seasonal and spatial variations in these chemical condition metrics were analyzed to elucidate the influence of meteorology and source proximity on gas–particle partitioning behavior.

$$\mathrm{GR} = \frac{[\mathrm{TA}] - 2[\mathrm{TS}]}{[\mathrm{TN}]} \tag{9}$$

$$\mathrm{AdjGR} = \frac{[\mathrm{NH_3}] + \left[\mathrm{NO_3^-}\right]}{[\mathrm{TN}]} \tag{10}$$

$$\mathrm{PNR} = \frac{\left[\mathrm{NH_4^+}\right]}{2\left[\mathrm{SO_4^{-2}}\right] + \left[\mathrm{NO_3^-}\right]} \tag{11}$$

$$\mathrm{TA/TS} = \frac{\left(\left[\mathrm{NH_4^+}\right] + [\mathrm{NH_3}]\right)}{\left[\mathrm{SO_4^{-2}}\right]} \tag{12}$$

$$\mathrm{NH_3/NH}_x = \frac{[\mathrm{NH_3}]}{[\mathrm{NH_3}] + \left[\mathrm{NH_4^+}\right]} \tag{13}$$

$$\mathrm{AN/PM_{2.5}} = \frac{\left(\left[\mathrm{NH_4^+}\right] + \left[\mathrm{NO_3^-}\right]\right)}{[\mathrm{PM_{2.5}}]} \tag{14}$$

where GR is the gas ratio; [TA] is the total ammonia concentration ($\mu molm^{-3}$), the sum of [NH_3] and [NH_4^+]; [TS] is the total sulfate concentration ($\mu molm^{-3}$), the sum of [SO_4^{-2}], [HSO_4^-], and [H_2SO_4]; [TN] is the total nitrate concentration ($\mu molm^{-3}$), the sum of

[NO_3^-] and [HNO_3]; AdjGR is an adjusted GR used examine $iPM_{2.5}$ sensitivity to NH_3 concentration in winter; PNR is the particle neutralization ratio; TA/TS is the mole ratio of total ammonia (NH_3 + NH_4^+ particulate) to particulate sulfate ratio; NH_3/NH_x is the gas-phase ammonia molar fraction ratio; AN/$PM_{2.5}$ is the fraction of ammonia sensitive $iPM_{2.5}$ (AN) to total $PM_{2.5}$.

$PM_{2.5}$ mass closure analysis was conducted to quantify the relative contributions of major chemical components to measured $PM_{2.5}$ mass and to evaluate the completeness of chemical speciation. Reconstructed $PM_{2.5}$ mass was calculated as the sum of major measured species, including organic carbon (OC), elemental carbon (EC), inorganic ions (NH_4^+, NO_3^-, SO_4^{2-}), elemental species. The reconstructed $PM_{2.5}$ mass was compared with gravimetrically measured $PM_{2.5}$ mass to assess closure performance. Agreement between measured and reconstructed mass was used as a quality check on chemical analyses and to identify dominant $PM_{2.5}$ components under varying atmospheric conditions. The mass closure results also provided insight into the relative importance of secondary inorganic versus organic fractions, informing interpretation of NH_3-driven $iPM_{2.5}$ formation potential in this rural, agricultural environment.

The combined evaluation of atmospheric chemical conditions and $PM_{2.5}$ mass closure forms the basis for subsequent thermodynamic equilibrium modeling and sensitivity analyses, linking observed chemical composition to mechanistic understanding of secondary aerosol formation.

2.5. ISOROPPIA-II Modleing

Thermodynamic equilibrium modeling was performed using the ISORROPIA-II model to examine gas–particle partitioning of inorganic aerosol species and to assess the sensitivity of secondary inorganic $PM_{2.5}$ formation to precursor availability and meteorological conditions [24]. ISORROPIA-II simulates multiphase equilibrium among major inorganic aerosol components (NH_4^+, NO_3^-, SO_4^{-2}, and associated cations) as a function of temperature, RH, and total (gas + particle) species concentrations.

The model was applied in forward mode, using measured ambient temperature and RH, along with observed total ammonia (NH_3 + NH_4^+), total nitrate (HNO_3 + NO_3^-), and particulate sulfate concentrations as inputs. Model outputs included predicted aerosol-phase concentrations, gas-phase partitioning, aerosol liquid water content, and hydrogen ion concentration. Sulfate was assumed to reside entirely in the particle phase due to the negligible vapor pressure of sulfuric acid.

Both stable and metastable thermodynamic states were evaluated, depending on ambient temperature and RH conditions, to account for potential phase-state variability of inorganic aerosols. Model performance was assessed through comparison of predicted and measured aerosol species concentrations.

In addition, sensitivity analyses were conducted by systematically varying total ammonia and total nitrate concentrations under representative temperature and relative humidity scenarios to quantify their influence on secondary inorganic $PM_{2.5}$ formation. The modeling results were used to interpret observed chemical conditions and to evaluate the extent to which NH_3 availability constrained secondary aerosol formation in the near-field of a poultry production facility.

2.6. Statistical Analysis

Statistical analyses were conducted to evaluate spatial and seasonal variations in precursor gas concentrations, $PM_{2.5}$ chemical composition, and atmospheric chemical condition metrics. Descriptive statistics, including mean and standard deviation, were calculated for all measured and derived variables. Data were grouped by season and monitoring station to assess temporal and spatial patterns associated with meteorological variability and source proximity.

Comparisons among seasons and sampling locations were performed using appropriate statistical tests based on data distribution and sample size. Correlation analyses were applied to examine relationships between precursor gases, $PM_{2.5}$ components, and chemical condition indicators relevant to secondary inorganic aerosol formation. All statistical analyses were conducted using R programming software (version 4.2.2), and results were interpreted at a significance level of $p < 0.05$.

3. Results and Discussion

3.1. Atmospheric NH_3, NO_2 and SO_2 Concentrations

Ammonia concentrations measured by the honeycomb denuders of the $PM_{2.5}$ speciation samplers, along with NO_2 and SO_2 concentrations measured by the Ogawa passive samplers, are summarized in Table 1. Key meteorological parameters, including ambient temperature, relative humidity, and wind speed, are reported in detail by Stratton [30].

Table 1. Mean ± SD of NH_3 concentration measured by Denuders of $PM_{2.5}$ speciation samplers and NO_2 and SO_2 concentrations measured by Ogawa passive samplers.

Season	Location	NH_3 (μgm^{-3})	NO_2 (μgm^{-3})	SO_2 (μgm^{-3})
Summer	ST1	0.843 ± 0.359 ^{b}	4.254 ± 1.298	0.117 ± 0.198
	ST3	0.953 ± 0.442 ^{b}	3.388 ± 0.515	0.000
	ST5	1.341 ± 0.623 ^{b}	2.662 ± 0.298	0.141 ± 0.298
	ST6	2.554 ± 1.22 ^{a}	3.739 ± 0.541	0.183 ± 0.550
Fall	ST1	1.038 ± 0.615	5.485	0.179
	ST3	0.743 ± 0.160	4.633	0.000
	ST5	0.753 ± 0.314	3.997	0.000
	ST6	1.2861 ± 0.351	0.341	0.342
Winter	ST1	0.603 ± 0.103 ^{a}	7.667 ± 0.850	0.417 ± 0.326
	ST3	0.336 ± 0.061 ^{b}	6.774 ± 0.861	0.456 ± 0.323
	ST5	0.476 ± 0.194 ^{a,b}	5.776 ± 1.91	0.598 ± 0.457
	ST6	0.575 ± 0.106 ^{a}	7.031 ± 0.968	0.242 ± 0.099

Means with different letters within a season indicate significant difference at $p < 0.05$.

As shown in Table 1, ambient NH_3_concentrations at the research site were relatively low, which is attributed to the low bird population during the study period, ranging from 1355 to 1366 birds. Statistically significant differences in mean concentrations were observed among sampling stations and across seasons. Measured SO_2_concentrations were low overall, with lower values in summer and higher values in winter, as expected for this rural setting. In contrast, NO_2_concentrations were higher than anticipated and exhibited clear seasonal variability, with lower concentrations in summer and higher concentrations in winter.

3.2. Atmospheric Chemical Conditions

Atmospheric chemical conditions relevant to secondary $iPM_{2.5}$ formation were evaluated using a suite of established indicators (Equations (9)–(14)) describing NH_3 availability, aerosol neutralization, and precursor balance. These metrics were derived from measured concentrations of precursor gases and inorganic aerosol species and were examined as functions of season, sampling location, and wind direction. The means of the five chemical condition metrics for three seasons at different sampling stations are summarized in Table 2. Overall, the calculated indicators consistently reflected NH_3-rich but acid-limited conditions in the vicinity of the poultry production facility. Spatial and temporal variability in these metrics was strongly influenced by seasonal changes in meteorology and by the relative upwind or downwind positioning of sampling stations.

Table 2. Mean ± SD of the chemical condition metrics separated by season and location.

Season	Location	GR or AdjGR [1]	PNR	TA/TS	NH_3/NH_x	$AN/PM_{2.5}$
Summer	ST1	2.624 ± 1.619 [a,][2]	0.988 ± 1.651 [a]	28.590 ± NA [3]	0.984 ± 0.013	0.010 ± 0.011
	ST3	3.528 ± 1.973 [b]	0.591 ± 0.447 [b]	84.686 ± NA	0.981 ± 0.018	0.015 ± 0.015
	ST5	5.572 ± 1.886 [b]	1.062 ± 1.115 [a,b]	NA [4]	0.986 ± 0.110	0.008 ± 0.007
	ST6	9.683 ± 5.221 [b]	2.268 ± 1.088 [a]	NA	0.992 ± 0.006	0.004 ± 0.002
Fall	ST1	3.314 ± 0.932	0.365 ± NA	18.256 ± NA	0.954 ± 0.021	0.018 ± 0.024
	ST3	3.205 ± 1.247	0.087 ± 0.021	9.323 ± NA	0.972 ± 0.025	0.018 ± 0.017
	ST5	3.653 ± 1.532	0.164 ± NA	8.239 ± NA	0.972 ± 0.021	0.013 ± 0.018
	ST6	5.771 ± 2.067	1.964 ± NA	NA	0.977 ± 0.009	0.007 ± 0.003
Winter	ST1	1.133 ± 0.360	5.765 ± 4.701	NA	0.798 ± 0.075 [a]	0.036 ± 0.031
	ST3	1.855 ± 1.299	0.859 ± NA	NA	0.971 ± 0.006 [b]	0.002 ± 0.002
	ST5	2.213 ± 1.928	3.112 ± 2.284	NA	0.858 ± 0.069 [a,b]	0.020 ± 0.016
	ST6	2.378 ± 1.076	4.013 ± 3.112	74.722 ± 29.017	0.754 ± 0.163 [a]	0.042 ± 0.041

[1] only winter season, data are in AdjGR; [2] means with different letters within a season indicate significant difference at $p < 0.05$; [3] NA of SD indicates that TS was extremely low, only one TA/TS ratio was obtained such that no standard deviation was available; [4] NA of mean indicates that no TA/TS ratio was obtained for the sampling events due to unavailability of TS at the locations; Cells with no letter indicate that no statistically significant differences were detected or that statistical testing was not conducted due to insufficient sample size ($n = 1$).

As indicated by GR values, at all four stations, there was sufficient NH_3 to neutralize SO_4^{2-} and NO_3^- (GR > 1) for all three seasons. As for PNR values, particle neutralization potential was significantly higher in winter than in summer and autumn at all four sampling stations. Although ambient NH_3 was low in winter, high PNR values were observed due to low SO_4^{-2} and NO_3^- (Equation (11)) from low concentrations of the precursor gases SO_2 and NO_2. Moreover, extremely low SO_2 concentrations also led to the inability to calculate TA/TS (Equation (12)). More sample collection is needed to truly understand dynamic changes in particle neutralization potential and TA/TS ratio in this rural environment. As for NH_3/NH_x results, greater than 0.5 at all stations and in all three seasons indicates that there was a greater amount of NH_3 in the gas phase than NH_4^+ in the particle phase. This is more proof of insufficient precursor acid gases SO_2 and NO_x to neutralize gas phase NH_3. When examining the average $AN/PM_{2.5}$ ratio, it is observed that percentage of NH_3 sensitive $PM_{2.5}$ mass to total $PM_{2.5}$ mass was lower than 5% which is an indication that formation of secondary NH_3-related $PM_{2.5}$ was low.

3.2.1. Gas Ratio (GR and AdjGR)

The gas ratio (GR) and adjusted gas ratio (AdjGR) were used to assess NH_3 neutralization potential relative to sulfate and nitrate availability. Across most sampling events, GR values exceeded unity, indicating sufficient NH_3 to fully neutralize sulfate but limited availability of acidic nitrate precursors. AdjGR values exhibited similar seasonal trends, with higher values observed during summer and autumn and lower values during winter. These results suggest that $iPM_{2.5}$ formation in this rural environment was constrained primarily by the availability of acidic species rather than NH_3.

3.2.2. Particle Neutralization Ratio (PNR)

The particle neutralization ratio (PNR) The particle neutralization ratio (PNR) exhibited clear spatial and seasonal variability across the study area. PNR values were frequently below one during summer and fall at several stations, indicating NH_3-limited conditions under those periods. In contrast, higher PNR values (PNR > 1) were observed at specific locations during winter, particularly at downwind stations, reflecting episodic NH_3-rich conditions rather than uniform NH_3 limitation across all seasons and stations. These findings further support the conclusion that $iPM_{2.5}$ formation was acid-limited despite elevated ambient NH_3 concentrations.

3.2.3. NH_3/NH_x Ratio

The molar fraction of gas-phase ammonia (NH_3/NH_x) was consistently high, particularly at downwind stations during summer and autumn. Elevated NH_3/NH_x ratios indicate that a substantial portion of total ammonia remained in the gas phase rather than partitioning into particulate ammonium. This behavior reflects limited conversion of NH_3 to NH_4^+ due to insufficient acidic reactants and highlights the dominance of gas-phase NH_3 in the near-field of the poultry facility.

3.2.4. Total Ammonia to Total Sulfate Ratio (TA/TS)

The TA/TS ratio exceeded two for most sampling periods, indicating non-acidic aerosol conditions favorable for complete sulfate neutralization. However, the lack of corresponding increases in particulate nitrate suggests that nitrate formation was thermodynamically or kinetically constrained. TA/TS exhibited substantial spatial and seasonal variability. While TA/TS decreased during winter at some stations (e.g., ST1 and ST3), elevated winter TA/TS values were observed at other locations (notably ST6), resulting in winter TA/TS values that were comparable to or higher than those in summer and autumn. Overall, the data indicate that winter conditions were not uniformly associated with lower TA/TS across stations.

3.2.5. Ammonia-Sensitive $PM_{2.5}$ Fraction ($AN/PM_{2.5}$)

The fraction of ammonia-sensitive $PM_{2.5}$ ($AN/PM_{2.5}$) was consistently low across all seasons, typically accounting for only a small portion of total $PM_{2.5}$ mass. This finding indicates that variations in NH_3 emissions alone would be unlikely to substantially affect ambient $PM_{2.5}$ concentrations in this setting. Instead, $PM_{2.5}$ mass was dominated by non-ammonium components, particularly organic carbon, as confirmed by mass closure analysis.

Collectively, these atmospheric chemical condition metrics demonstrate that secondary inorganic $PM_{2.5}$ formation near the poultry production facility was primarily limited by acidic precursor availability rather than ammonia. The observed NH_3-rich, acid-limited environment provides important context for interpreting thermodynamic modeling results and assessing the effectiveness of NH_3-focused mitigation strategies in rural agricultural regions.

3.3. *$PM_{2.5}$ Mass Closure*

$PM_{2.5}$ mass closure analysis was conducted to assess the relative contributions of major chemical components and to evaluate the completeness and consistency of the chemical speciation measurements. The analysis focused on reconstructed $PM_{2.5}$ mass derived from the sum of measured species, including organic carbon (OC), elemental carbon (EC), inorganic ions (SO_4^{-2}, NO_3^-, NH_4^+), elemental constituents, and other inorganic components.

Initial comparisons between reconstructed $PM_{2.5}$ mass and gravimetrically measured $PM_{2.5}$ mass revealed substantial discrepancies for a number of sampling events, with reconstructed mass occasionally exceeding measured $PM_{2.5}$. Such inconsistencies are commonly attributed to uncertainties associated with filter handling, conditioning, and weighing, particularly under low-mass loading conditions typical of rural environments.

To avoid propagation of these uncertainties, subsequent mass closure analysis emphasized the relative chemical composition of $PM_{2.5}$ rather than absolute mass agreement.

Seasonal mean concentrations of $PM_{2.5}$ components were calculated for each monitoring station and are summarized in Table 3. Across all seasons and stations, $PM_{2.5}$ was dominated by organic carbon, accounting for the majority of reconstructed mass. In contrast, secondary inorganic aerosol components (NH_4^+, NO_3^-, and SO_4^{-2}) contributed only a minor fraction of total $PM_{2.5}$ mass. This compositional pattern was consistent across summer, autumn, and winter, despite seasonal variability in precursor gas concentrations and meteorological conditions.

Table 3. Mean ± SD for $PM_{2.5}$ and its Components in μgm^{-3}.

Season *	**Location**	**$PM_{2.5}$**	**OC**	**EC**	**SO_4^{-2}**	**NO_3^-**	**NH_4^+**	**Elements**	**Inorganics ****
Summer	ST1	$6.584 \pm 1.559^{a,b}$	5.256 ± 1.885	0.001 ± 0.001	0.038 ± 0.094	0.523 ± 1.123	0.012 ± 0.012	0.422 ± 0.145	0.189 ± 0.181
	ST3	6.146 ± 1.977^{a}	6.455 ± 2.312	0.001 ± 0.001	0.037 ± 0.078	0.448 ± 0.664	0.013 ± 0.007	0.398 ± 0.179	0.141 ± 0.082
	ST5	9.772 ± 4.255^{b}	5.907 ± 1.677	0.001 ± 0.000	0.000	0.910 ± 1.020	0.020 ± 0.026	0.507 ± 0.168	0.129 ± 0.057
	ST6	$8.234 \pm 1.425^{a,b}$	6.457 ± 1.035	0.001 ± 0.001	0.001 ± 0.003	0.126 ± 0.176	0.016 ± 0.005	0.436 ± 0.099	0.083 ± 0.023
Fall	ST1	7.845 ± 2.444	8.251 ± 2.982	0.442 ± 0.284	0.167 ± 0.207	0.130 ± 1.099	0.053 ± 0.040	0.435 ± 0.149	0.121 ± 0.073
	ST3	6.515 ± 2.221	9.639 ± 3.356	0.552 ± 0.283	0.607 ± 0.506	0.120 ± 0.658	0.023 ± 0.013	0.374 ± 0.187	0.091 ± 0.049
	ST5	7.333 ± 4.143	8.878 ± 3.898	0.472 ± 0.427	0.123 ± 0.214	0.050 ± 0.087	0.020 ± 0.010	0.352 ± 0.142	0.067 ± 0.036
	ST6	7.041 ± 3.860	8.232 ± 4.485	0.432 ± 0.437	0.000	0.023 ± 0.040	0.030 ± 0.010	0.435 ± 0.292	0.086 ± 0.034
Winter	ST1	7.701 ± 2.500	7.100 ± 2.937	0.145 ± 0.284	0.000 ± 0.204	$0.106 \pm 1.114^{a,b}$	$0.116 \pm 0.038^{a,b}$	0.463 ± 0.106	0.105 ± 0.008
	ST3	7.574 ± 2.312	8.134 ± 3.405	0.090 ± 0.283	0.000 ± 0.509	0.006 ± 0.671^{a}	0.010 ± 0.014^{a}	0.462 ± 0.189	0.066 ± 0.049
	ST5	7.534 ± 1.892	6.564 ± 2.275	0.002 ± 0.001	0.000	$0.097 \pm 0.106^{a,b}$	$0.063 \pm 0.044^{a,b}$	0.430 ± 0.073	0.198 ± 0.289
	ST6	8.591 ± 5.025	7.060 ± 1.881	0.151 ± 0.332	0.022 ± 0.032	0.144 ± 0.107^{b}	0.160 ± 0.127^{b}	0.405 ± 0.057	0.308 ± 0.293

* For each season, differences among locations were evaluated using one-way ANOVA followed by post hoc multiple comparison tests. Within the same season and chemical component, means followed by different lowercase letters are significantly different at $p < 0.05$. Absence of letter notation indicates that no statistically significant differences were detected among locations or that statistical testing was not conducted due to limited sample size; ** inorganics include Na^+, Ca^{+2}, Cl^-, Mg^{+2}, and K.

The limited contribution of inorganic ions to $PM_{2.5}$ mass is consistent with the atmospheric chemical condition analysis, which indicated NH_3-rich but acid-limited conditions near the poultry production facility. Even during winter, when thermodynamic conditions were more favorable for ammonium nitrate formation, inorganic aerosol mass remained small relative to organic components. These findings suggest that $PM_{2.5}$ in this rural agricultural environment was largely influenced by organic sources rather than secondary inorganic formation driven by ammonia emissions.

Figures 3–5 illustrate the seasonal $PM_{2.5}$ chemical speciation mass fractions for summer, autumn, and winter, respectively. Across all monitoring stations and seasons, organic carbon (OC) was the dominant $PM_{2.5}$ component, accounting for approximately 80–93% of the total $PM_{2.5}$ mass. This contribution is substantially higher than that reported by Li et al. [33], who observed OC fractions of 50–55% at four ambient stations surrounding a commercial egg production facility in North Carolina. Primary OC is commonly associated with biomass combustion and traffic emissions, whereas secondary OC forms through atmospheric oxidation of volatile organic compounds (VOCs) emitted primarily from vegetation [34–36]. Previous studies have shown that OC and elemental carbon together can contribute between 10% and 80% of $PM_{2.5}$ mass across diverse environments, including urban regions in Europe, California, and China [35–37]. In a European urban environment influenced by strong biogenic emissions, Saarikoski et al. [34] reported that approximately 64% of OC was secondary in origin.

In contrast, the combined mass fractions of inorganic secondary aerosol components (NH_4^+, SO_4^{-2}, and NO_3^-) were consistently low, ranging from 0% to 1% across all stations (Figure 3). Despite summer-time atmospheric chemical indicators (GR and PNR) suggesting sufficient NH_3 availability for aerosol neutralization, the contribution of NH_3-related secondary iPM$_{2.5}$ remained minimal, as reflected by AN/PM$_{2.5}$ values below 0.03. TA/TS values were consistently greater than 2 across all seasons and locations (Table 2), suggesting NH$_3$-rich or weakly acidic conditions in which particulate sulfate was fully neutralized and additional NH$_3$ was available for potential nitrate formation. These results suggest that the small amount of iPM$_{2.5}$ formed at the site was primarily associated with ammonium nitrate formation via reactions between NH$_3$ and nitric acid, rather than sulfate-driven processes.

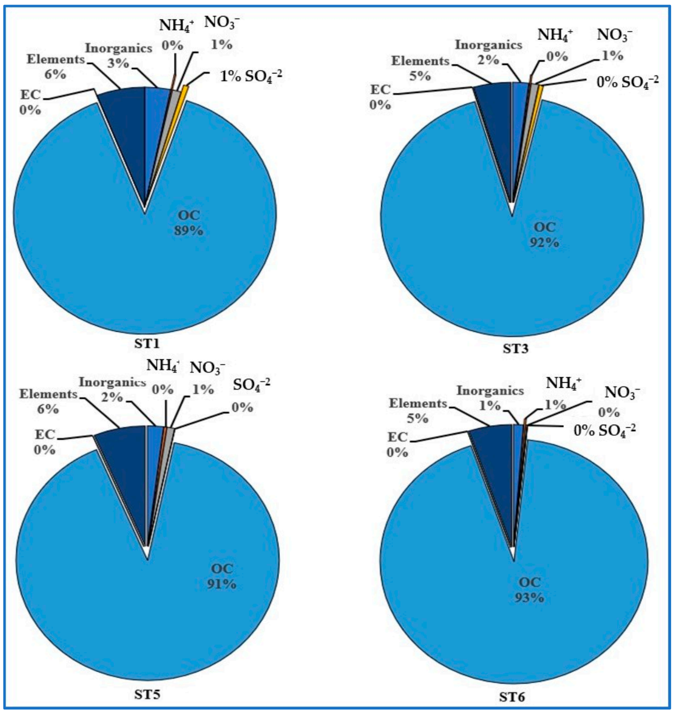

Figure 3. PM$_{2.5}$ chemical speciation mass fractions in Summer; inorganics include Na$^+$, Ca^{2+}, Cl$^-$, Mg^{+2}, and K.

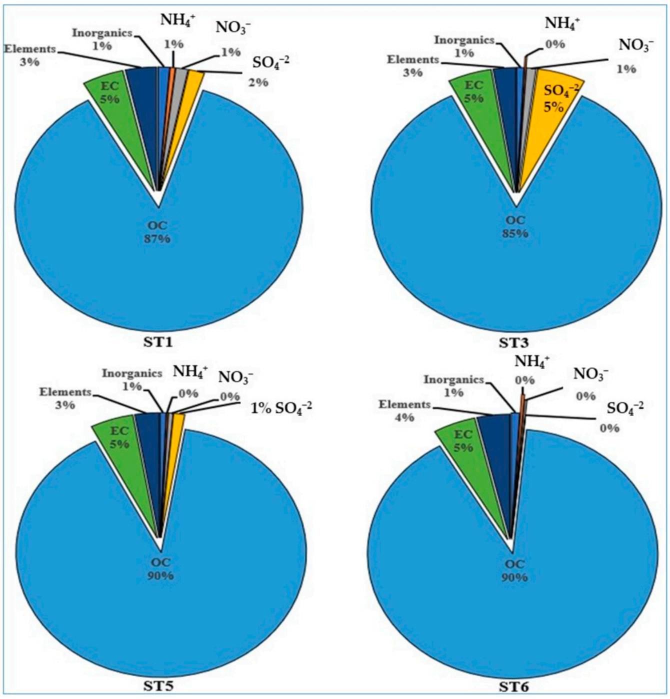

Figure 4. PM$_{2.5}$ chemical speciation mass fractions in Fall (**right**); inorganics include Na$^+$, Ca^{2+}, Cl$^-$, Mg^{+2}, and K.

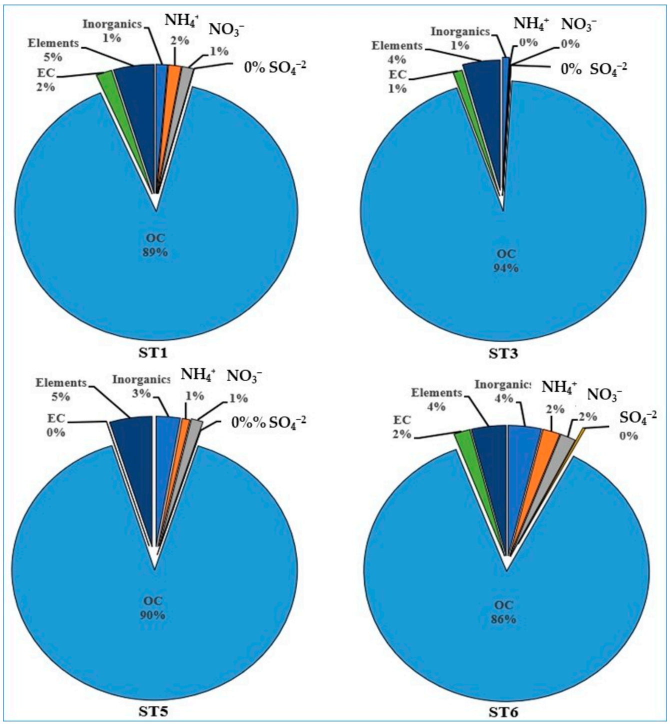

Figure 5. $PM_{2.5}$ chemical speciation mass fractions in Winter; inorganics include Na^+, Ca^{2+}, Cl^-, Mg^{+2}, and K.

Overall, the $PM_{2.5}$ mass closure results reinforce the conclusion that secondary inorganic $PM_{2.5}$ formation played a minor role in determining ambient $PM_{2.5}$ levels at the study site. The dominance of organic matter has important implications for interpreting ammonia mitigation strategies, as reductions in NH_3 emissions alone are unlikely to substantially reduce $PM_{2.5}$ mass under the observed chemical and meteorological conditions.

3.4. *Thermodynamic Equilibrium Modeling*

The ISORROPIA-II thermodynamic equilibrium model was applied to interpret observed gas–particle partitioning behavior and to evaluate the sensitivity of secondary $iPM_{2.5}$ formation to precursor availability under varying atmospheric conditions. Model simulations were conducted using measured temperature, RH, total ammonia (NH_3 + NH_4^+), total nitrate (HNO_3 + NO_3^-), and particulate sulfate concentrations.

3.4.1. Response of $iPM_{2.5}$ to Total Ammonia

Sensitivity analyses examining the response of $iPM_{2.5}$ to changes in total ammonia are shown in Figure 6. Across most temperature and RH scenarios, increases in total ammonia resulted in only modest increases in particulate ammonium and total $iPM_{2.5}$ mass. This limited response reflects the acid-limited atmospheric conditions identified from field measurements, where excess NH_3 was not efficiently converted to particulate ammonium due to insufficient sulfate and nitrate availability.

Under wintertime conditions, when lower temperatures favored ammonium nitrate stability, increased total ammonia led to slightly higher predicted particulate nitrate formation. Nevertheless, the absolute contribution of NH_3-related $iPM_{2.5}$ remained small relative to total $PM_{2.5}$ mass, consistent with mass closure results showing dominance of organic components.

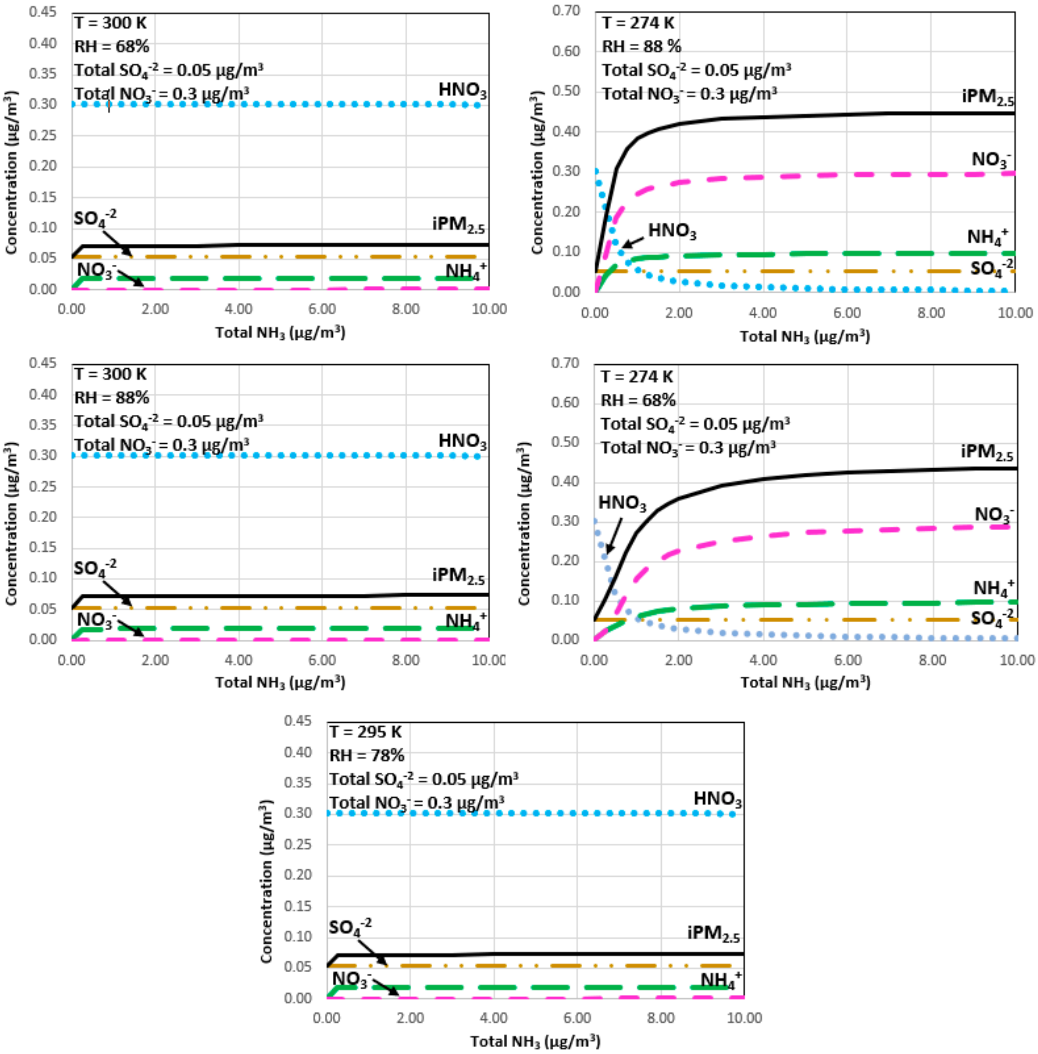

Figure 6. Responses of $iPM_{2.5}$ components to total NH_3 under five different T and RH conditions.

3.4.2. Response of $iPM_{2.5}$ to Total Nitrate

In contrast, $iPM_{2.5}$ formation exhibited greater sensitivity to increases in total nitrate than to ammonia, particularly under low-temperature conditions (Figure 7). Model simulations demonstrated that augmenting total nitrate resulted in pronounced increases in particulate nitrate when sufficient ammonia was present, even in environments with low sulfate concentrations. This response highlights nitric acid availability as a key limiting factor controlling $iPM_{2.5}$ formation at the study site.

These findings indicate that secondary inorganic aerosol formation in this rural agricultural environment is governed primarily by the availability of acidic precursor gases rather than ammonia emissions alone. The modeling results further suggest that reductions in NH_3 emissions, in the absence of concurrent changes in NO_x or SO_2, are unlikely to yield substantial decreases in ambient $PM_{2.5}$ concentrations.

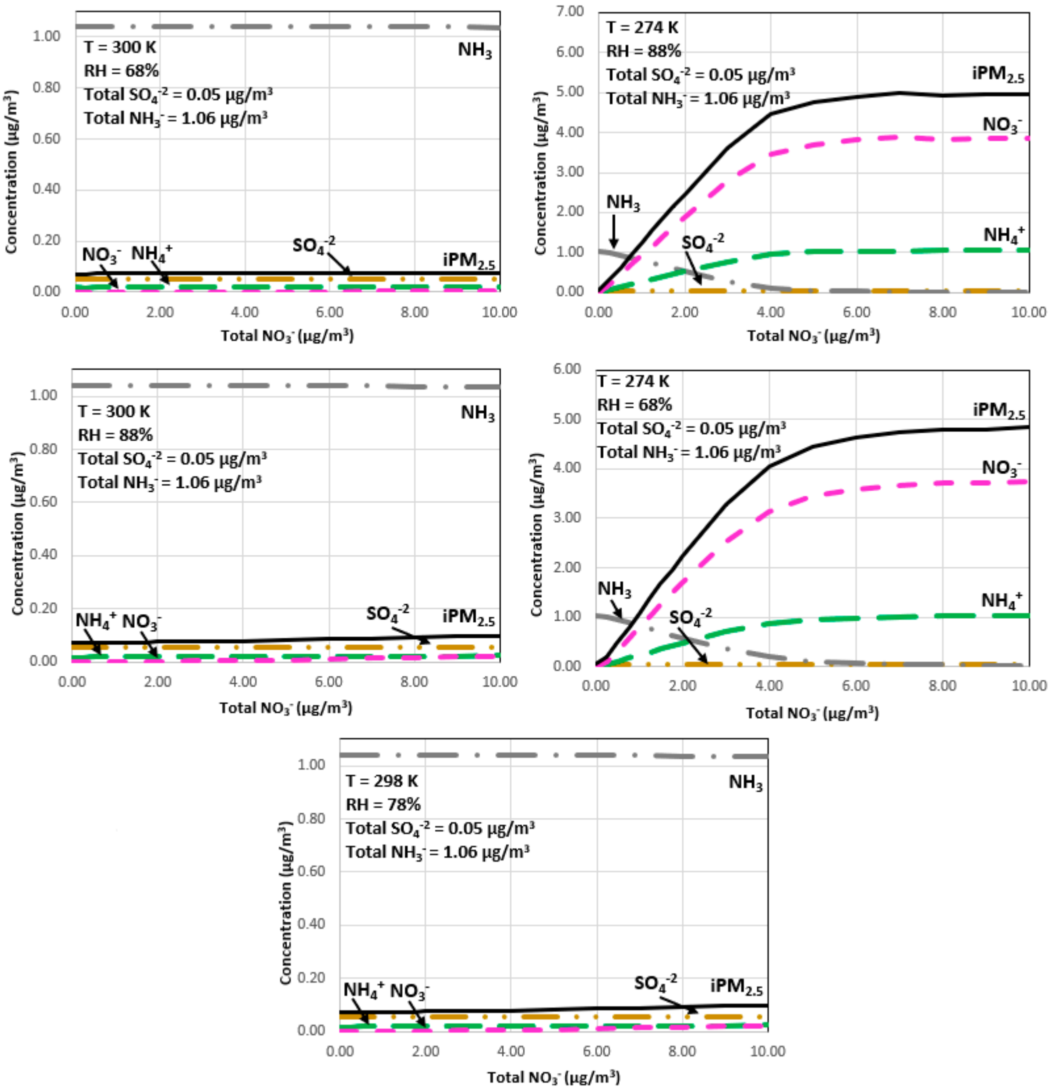

Figure 7. Responses of $iPM_{2.5}$ components to total NO_3^- under five different T and RH conditions.

4. Conclusions

This study investigated the formation potential of secondary $iPM_{2.5}$ in the near-field of a poultry production facility using multi-season field measurements and thermodynamic equilibrium modeling. The results provide new insight into the role of agricultural NH_3 emissions in a rural, acid-limited environment.

Atmospheric chemical condition analyses consistently indicated NH_3-rich but acid-limited conditions across all seasons. Elevated adjusted gas ratio (AdjGR) and gas-phase ammonia fraction (NH_3/NH_x), coupled with low particle neutralization ratio (PNR) and low ammonia-sensitive $PM_{2.5}$ fraction ($AN/PM_{2.5}$), demonstrate that excess ambient NH_3 was not efficiently converted to particulate ammonium due to limited availability of acidic precursor gases. These conditions persisted despite seasonal variability in meteorology and emission strength.

$PM_{2.5}$ mass closure analysis revealed that organic carbon dominated ambient $PM_{2.5}$ composition, accounting for approximately 80–93% of total $PM_{2.5}$ mass. In contrast, secondary inorganic components (NH_4^+, NO_3^-, and SO_4^{2-}) contributed only a minor fraction, confirming that $iPM_{2.5}$ formation played a limited role in determining $PM_{2.5}$ mass at the study site. This compositional dominance of organic aerosols further constrained the influence of NH_3-driven inorganic aerosol formation.

Thermodynamic equilibrium modeling using ISORROPIA-II supported the field-based findings and demonstrated that $iPM_{2.5}$ formation was weakly sensitive to increases in total ammonia but strongly sensitive to increases in total nitrate, particularly under colder and more humid conditions. These results indicate that nitric acid availability, rather than NH_3 emissions alone, was the primary limiting factor controlling secondary inorganic aerosol formation in this rural agricultural setting.

Collectively, these findings suggest that mitigation strategies targeting NH_3 emissions alone are unlikely to yield substantial reductions in ambient $PM_{2.5}$ concentrations in regions characterized by low SO_2 and NO_x emissions. Instead, effective $PM_{2.5}$ management in agricultural environments requires an integrated understanding of precursor balance, atmospheric chemistry, and organic aerosol contributions. Future studies should further investigate the interactions between organic aerosols and inorganic partitioning processes, as well as the role of regional transport of acidic precursors in modulating $iPM_{2.5}$ formation near animal feeding operations.

Author Contributions: Conceptualization, B.S. and L.W.-L.; methodology, B.S. and L.W.-L.; project administration, L.W.-L.; data analysis, B.S. and L.W.-L., data interpretation, B.S., L.W.-L., W.S., S.S., J.C. and K.A.; writing—original draft preparation, B.S. and L.W.-L.; writing—review and editing, B.S., L.W.-L. and S.S.; funding acquisition, L.W.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by NSF Award No. CBET-1804720.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors gratefully acknowledge the team at RTI International, Tracy Dombek, Sophie Brenner, Katarina Lindskog, Nicole Manalis, Jason McNeill, Andrea McWilliams, and Frank Weber, for their invaluable support in the chemical analysis of $PM_{2.5}$ speciation samples and passive gas samples. This study was made possible through the generous assistance of Lisa Wilson and the staff of the North Carolina Department of Agriculture Piedmont Research Station Poultry Unit, who provided access to the facility and logistical support during field sampling. The authors also thank Justin Macialek and Jay Campbell for their help with transporting and deploying heavy sampling equipment, and Phil Harris for assistance with sampler repair and maintenance. Special thanks are extended to Bin Cheng, Suraiya Akter, and Sam Cherotich for their extensive contributions to field sampling and modeling efforts, and to Andrew Grieshop and his research team at NC State for providing access to instrumentation for $PM_{2.5}$ carbon analysis.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Shaver, S.; Leytem, A.; Burns, R.; Xin, H.; Wang-Li, L.; Moody, L.; Embertson, N.; Fabian-Wheeler, E. Ammonia Emissions: What to Know Before You Regulate. Prepared by the United States Department of Agriculture, Agricultural Air Quality Task Force. 2014. Available online: https://www.nrcs.usda.gov/sites/default/files/2022-10/AAQTF-Accomplishments-Ammonia-White-Paper.pdf (accessed on 8 February 2026).
2. Behera, S.; Sharma, M.; Aneja, V.; Balasubramanian, R. Ammonia in the atmosphere: A review on emissions sources, atmospheric chemistry and deposition on terrestrial bodies. *Environ. Sci. Pollut. Res.* **2013**, *20*, 8092–8131. [CrossRef] [PubMed]
3. Van Damme, M.; Clarisse, L.; Franco, B.; Sutton, M.; Erisman, J.; Kruit, R.; Zanten, M.; Whitburn, S.; Hadji-Lazaro, J.; Hurtmans, D.; et al. Global, regional and national trends of atmospheric ammonia derived from a decadal (2008–2018) satellite record. *Environ. Res. Lett.* **2021**, *16*, 055017. [CrossRef]
4. Elliot, H.A.; Collins, N.E. Factors affecting ammonia release in broiler houses. *Trans. ASAE* **1982**, *25*, 413–418. [CrossRef]

5. Sommer, S.G.; Olesen, J.E.; Christensen, B.T. Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry. *J. Agric. Sci.* **1991**, *117*, 91–100. [CrossRef]
6. Jiang, J.; Stevenson, D.; Uwizeye, A.; Tempio, G.; Sutton, M. A climate-dependent global model of ammonia emissions from chicken farming. *Biogeosciences* **2021**, *18*, 135–158. [CrossRef]
7. Sutton, M.A.; Fowler, D.; Moncrieff, J.B. The exchange of atmospheric ammonia with vegetated surfaces. I: Unfertilized vegetation. *Q. J. R. Meteorol. Soc.* **1993**, *119*, 1023–1045. [CrossRef]
8. Guthrie, S.; Giles, S.; Dunkerley, F.; Tabaqchali, H.; Harshfield, A.; Ioppolo, B.; Manville, C. *Impact of Ammonia Emissions from Agriculture on Biodiversity*; RAND Corporation: Santa Monica, CA, USA, 2018; p. 76.
9. Bouwman, A.F.; Van Vuuren, D.P.; Derwent, R.G.; Posch, M. A global analysis of acidification and eutrophication of terrestrial ecosystems. *Water Air Soil Pollut.* **2002**, *141*, 349–382. [CrossRef]
10. Bobbink, R.; Hicks, K. Factors affecting N deposition impacts on biodiversity: An overview. In *Nitrogen Deposition, Critical Loads and Biodiversity*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 127–138. [CrossRef]
11. Dawson, J.P.; Adams, P.J.; Pandis, S.N. Sensitivity of PM 2.5 to climate in the Eastern US: A modeling case study. *Atmos. Chem. Phys.* **2007**, *7*, 4295–4309. [CrossRef]
12. Bauer, S.; Tsigaridis, K.; Miller, R. Significant atmospheric aerosol pollution caused by world food cultivation. *Geophys. Res. Lett.* **2016**, *43*, 5394–5400. [CrossRef]
13. Cheng, B.; Wang-Li, L.; Meskhidze, N.; Classen, J.; Bloomfield, P. Partitioning of NH_3-NH_4^+ in the Southeastern U.S. *Atmosphere* **2021**, *12*, 1681. [CrossRef]
14. Cheng, B.; Wang-Li, L.; Meskhidze, N.; Classen, J.; Bloomfield, P. Spatial and temporal variations of $PM_{2.5}$ mass closure and inorganic $PM_{2.5}$ in the Southeastern U.S. *Environ. Sci. Pollut. Res.* **2019**, *26*, 33181–33191. [CrossRef] [PubMed]
15. Cheng, B.; Wang-Li, L. Responses of Secondary Inorganic $PM_{2.5}$ to Precursor Gases in an Ammonia Abundant Area in North Carolina. *Aerosol Air Qual. Res.* **2019**, *19*, 1126–1138. [CrossRef]
16. Li, Q.-F.; Wang-Li, L.; Liu, Z.; Jayanty, R.K.M.; Shah, S.B.; Bloomfield, P. Ammonia concentrations and modeling of inorganic particulate matter in the vicinity of an egg production facility in Southeastern USA. *Environ. Sci. Pollut. Res.* **2014**, *21*, 4675–4685. [CrossRef] [PubMed]
17. Li, Q.-F.; Wang-Li, L.; Liu, Z.; Jayanty, R.K.M.; Shah, S.B.; Bloomfield, P. Major Ionic Composition of Fine Particulate Matter in an Animal Feeding Operation Facility and its Vicinity. *J. Air Waste Manag. Assoc.* **2014**, *21*, 1279–1287. [CrossRef]
18. Walker, J.T.; Robarge, W.P.; Shendrikar, A.; Kimball, H. Inorganic PM 2.5 at a US agricultural site. *Environ. Pollut.* **2006**, *2*, 258–271. [CrossRef]
19. World Health Organization. *Health Effects of Particulate Matter*; World Health Organization: Geneva, Switzerland, 2013.
20. Lelieveld, J.; Evans, J.S.; Fnais, M.; Giannadaki, D.; Pozzer, A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **2015**, *525*, 367–371. [CrossRef]
21. Malley, C.; Hicks, W.; Kulyenstierna, C.; Michalopoulou, E.; Molotoks, A.; Slater, J.; Heaps, C.; Ulloa, S.; Veysey, J.; Shindell, D. Integrated assessment of global climate, air pollution, and dietary, malnutrition and obesity health impacts of food production and consumption between 2014 and 2018. *Environ. Res. Commun.* **2021**, *3*, 075001. [CrossRef]
22. Seinfeld, J.H.; Pandis, S.N. *Atmospheric Chemistry and Physics, from Air Pollution to Climate Change*; Wile-Interscience: New York, NY, USA, 1998.
23. Xu, J.; Chen, J.; Wang, G.; Yu, G.; Li, H.; Huo, J.; Lin, Y.; Fu, Q.; Guo, H.; Deng, C.; et al. Importance of gas-particle partitioning of ammonia in haze formation in the rural agricultural environment. *Atmos. Chem. Phys.* **2020**, *20*, 7259–7269. [CrossRef]
24. Fountoukis, C.; Nenes, A. ISORROPIA II: A computationally efficient thermodynamic equilibrium model for K^+–Ca^{2+}–Mg^{2+}–NH^{4+}–Na^+–$SO_4{}^{2-}$–NO^{3-}–Cl^-–H_2O aerosols. *Atmos. Chem. Phys.* **2007**, *7*, 4639–4659. [CrossRef]
25. Wu, S.-Y.; Hu, J.-L.; Zhang, Y.; Aneja, V.P. Modeling atmospheric transport and fate of ammonia in North Carolina-Part II: Effect of ammonia emissions on fine particulate matter formation. *Atmos. Environ.* **2007**, *42*, 3437–3451. [CrossRef]
26. Silvern, R.; Jacob, D.; Kim, P.; Marais, E.; Turner, J.; Campuzano-Jost, P.; Jimenez, J. Inconsistency of ammonium–sulfate aerosol ratios with thermodynamic models in the eastern US: A possible role of organic aerosol. *Atmos. Chem. Phys.* **2017**, *17*, 5107–5118. [CrossRef]
27. Guo, H.; Nenes, A.; Weber, R.J. The underappreciated role of nonvolatile cations on aerosol ammonium-sulfate molar ratios. *Atmos. Chem. Phys.* **2018**, *18*, 17307–17323. [CrossRef]
28. Cheng, B.; Wang-Li, L.; Meskhidze, N.; Classen, J.; Bloomfield, P. Performance of a Thermodynamic Model for Predicting Inorganic Aerosols in the Southeastern U.S. *Atmosphere* **2022**, *13*, 1977. [CrossRef]
29. Makar, P.A.; Moran, M.D.; Zheng, Q.; Cousineau, S.; Sassi, M.; Duhamel, A.; Besner, M.; Davignon, D.; Crevier, L.P.; Bouchet, V.S. Modelling the impacts of ammonia emissions reductions on North American air quality. *Atmos. Chem. Phys. Discuss.* **2009**, *2*, 5371–5422. [CrossRef]

30. Stratton, B. Formation of Secondary Inorganic $PM_{2.5}$ as Impacted by Ammonia Concentrations near an Animal Feeding Operation. Master's Thesis, North Carolina State University, Raleigh, NC, USA, 2023. Available online: https://repository.lib.ncsu.edu/server/api/core/bitstreams/3e77696b-d743-4d0f-9111-81c8eea0df98/content (accessed on 8 February 2026).
31. CFR. *Reference Method for the Determination of Fine Particulate Matter as $PM_{2.5}$ in the Atmosphere; 40 CFR, Part 50, Appendix L*; Government Printing Office: Washington, DC, USA, 2026.
32. EPA. Evaluation of $PM_{2.5}$ Chemical Speciation Samplers for Use in the EPA National $PM_{2.5}$ Chemical Speciation Network. Volume I—Introduction, Results and Conclusions. 2001. Available online: https://nepis.epa.gov/Exe/ZyNET.exe/P100D71X.txt?ZyActionD=ZyDocument&Client=EPA&Index=2000%20Thru%202005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C00THRU05%5CTXT%5C00000029%5CP100D71X.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=2 (accessed on 8 February 2026).
33. Li, Q. Particulate Matter from an Egg Production: Emission, Chemistry and Local Dispersion. Ph.D. Thesis, North Carolina State University, Raleigh, NC, USA, 2012.
34. Saarikoski, S.; Timonen, H.; Saarnio, K.; Aurela, M.; Jarvi, L.; Keronen, P.; Kerminen, V.-M.; Hillamo, R. Sources of organic carbon in fine particulate matter in northern European urban air. *Atmos. Chem. Phys.* **2008**, *8*, 6281–6295. [CrossRef]
35. Harrison, R.; Jones, A.; Lawrence, R. Major Component composition of PM_{10} and $PM_{2.5}$ from roadside and urban background sites. *Atmos. Environ.* **2004**, *38*, 4351–4538. [CrossRef]
36. Wang, G.; Cheng, S.; Li, J.; Lang, J.; Wen, W.; Yang, X.; Tian, L. Source apportionment and seasonal variation of $PM_{2.5}$ carbonaceous aerosol in the Beijing-Tianjin-Hebei Region of China. *Environ. Monit. Assess.* **2015**, *187*, 143. [CrossRef]
37. Na, K.; Sawant, A.; Song, C.; Cocker, D., III. Primary and secondary carbonaceous species in the atmospheric of Western Riverside County, California. *Atmos. Environ.* **2004**, *38*, 1345–1355. [CrossRef]