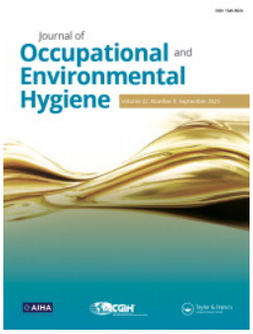

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REPORT

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Field comparison of inhalable air samplers for the determination of occupational exposure to inhalable aerosols and soluble proteins in food production

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ABSTRACT

This study assessed the performance of the Institute of Occupational Medicine (IOM) and Gesamtstaubprobenahme (GSP) personal inhalable aerosol samplers in measuring aerosol and soluble protein (SP) concentrations across 12 food industry environments. A total of 193 sampling pairs (GSP and IOM) were analyzed for inhalable aerosols, and 185 sampling pairs for SP. Median aerosol concentrations ranged from 0.2 mg/m^3 in snacks, nuts, and chips production to 5.6 mg/m^3 in spreads production. The IOM sample had a median aerosol concentration of 1.8 mg/m^3, while the GSP had a slightly lower median of 1.4 mg/m^3, generally collecting 17% less inhalable aerosol than the IOM in most environments. The IOM also included wall deposits in its gravimetric determinations, contributing an additional 10–30% to the overall aerosol concentrations. For SP concentrations, the IOM measured higher aerosol concentrations in environments with a particle size distribution dominated by larger particles, while the GSP showed higher SP concentrations in environments dominated by smaller, respirable particles. The Tobit mixed-effect models showed that the IOM had statistically significantly higher aerosol concentrations compared to the GSP, but significantly lower SP concentrations than the GSP. However, these differences between the samplers were relatively small, suggesting that in occupational hygiene practices, both samplers can be used.

KEYWORDS

Aerosol monitoring; food industry; GSP sampler; IOM sampler; protein monitoring

Introduction

Respiratory illnesses are a serious concern for workers in the food processing industry, where exposure to airborne particles can lead to occupational asthma and rhinitis (Aresery and Lehrer 2002; Jeebhay and Baatjies 2022). It is estimated that 10% to 25% of all cases of occupational asthma and rhinitis are directly linked to workplace exposure to food-related airborne particles (Kogevinas et al. 2007). The prevalence of these conditions varies widely across different food processing environments, ranging from 3% to 10% among green coffee bean workers to as high as 4% to 36% among shellfish processing workers (Baatjies and Jeebhay 2013; Cartier 2010).

Accurately assessing worker exposure to these inhalable aerosols is important for ensuring workplace safety. Personal inhalable aerosol samplers, such as the Institute of Occupational Medicine (IOM) (Mark and Vincent 1986) and Gesamtstaubprobenahme (GSP) (Siekmann et al. 1988) samplers, are essential tools for this purpose. Several studies have evaluated the performance of IOM and GSP samplers, both in controlled wind tunnel studies and field studies. Wind tunnel studies demonstrate a strong correlation between the IOM and GSP samplers and sampling efficiencies that matched the current inhalability criterion relatively well (Aizenberg et al. 2000; Kenny et al. 1999; Sleeth and Vincent 2012). In contrast, field studies have reported more significant differences between parallel IOM and GSP sampler measurements than those observed under controlled conditions (Kock et al. 2015; Lee et al. 2011; Zugasti et al. 2012).

While previous studies offer useful insights into the performance of IOM and GSP samplers for inhalable aerosols, there is limited direct comparison of their effectiveness in sampling soluble protein (SP) specifically within the food industry. Both the GSP and IOM

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inhalable samplers have been tested in laboratory studies and found to sample aerosol particles in accordance with the inhalable convention, which is based primarily on mouth breathing data and aerosols with aerodynamic diameters (d_{ae}) smaller than 100 µm (CEN 1993; ISO 1995). While the convention does not specify efficiency for particles larger than 100 µm, a laboratory study by Aizenberg et al. demonstrated that both samplers captured particles above this size (Aizenberg et al. 2001). In this study, the sampling efficiency of the IOM sampler was shown to significantly increase with aerodynamic particle size when tested for particles above $d_{ae} = 96$ µm, while the sampling efficiency of the GSP did not significantly change with particle size (Aizenberg et al. 2001). In addition, a laboratory study showed that the IOM sampler tended to oversample larger particles ($d_{ae} > 60$ µm) compared to the GSP sampler (Kenny et al. 1999).

Current occupational exposure limits for flour dust may not sufficiently protect bakers from conditions like rhinitis and asthma, given the complex mix of allergens in bakery aerosols. These allergens include substances such as α-amylase, mites, soy, and newer allergens like quinoa (Brisman et al. 2000; Guarnieri et al. 2019; Houba et al. 1998; Raulf-Heimsoth et al. 2017; Storaas et al. 2005). Wheat flour alone contains more than 100 potential allergens (Bittner et al. 2008), and flour dust can also provoke non-allergic reactions, such as itching (Jung and Park 1999; Marraccini et al. 2008). Monitoring exposure to specific allergens is difficult due to their variety, the growing number of allergens, and the high costs of available analytical methods. Instead, measuring the SP concentration using personal inhalable aerosol samplers and commercial protein assay kits may provide a more comprehensive and cost-effective strategy for assessing workplace exposure in food manufacturing environments.

This study aimed to investigate the performance of IOM and GSP samplers concerning sampling of inhalable aerosols and SP across a diverse range of food environments. By evaluating their effectiveness in sampling these airborne contaminants in various food production environments, this study provides insights for selecting the most appropriate sampling method for assessing worker exposure to inhalable aerosol and SP in the dry powdered food industry.

Methods

Sampling procedure

Sampling sites

Twelve different dry food manufacturing facilities in Norway participated in this study, including those that produced baked goods, coffee, instant powdered consumer foods, spices, confectioneries and chocolate, spreads, snacks, nuts, and chips. The measuring campaigns were conducted between February 2022 and May 2023.

Work tasks with potential aerosol exposures were identified and chosen in collaboration with the occupational safety and health management/manager at each production facility.

The inhalable aerosol data for the GSP sampler from powder consumer product production was previously published in Darbakk et al. (2024).

Sampling equipment

Two types of inhalable aerosol samplers were utilized in this study. A GSP (GSA Messgerätebau, Ratingen, Germany) inhalable aerosol sampler was equipped with a 37 mm diameter polyvinyl chloride (PVC) filter with a 5 µm pore size (Merck Millipore, Burlington, MA, USA). The sampler was connected to a Casella APEX 2 Pro (Casella UK, Bedford, UK) air sampling pump calibrated to maintain an airflow rate of 3.5 L/min. Additionally, an IOM (Institute of Occupational Medicine, Edinburgh, UK) inhalable dust plastic sampler with a stainless-steel cassette was equipped with a 25 mm diameter PVC filter, also with a 5 µm pore size. This sampler was connected to a Casella APEX 2 Pro air sampling pump, calibrated to an airflow rate of 2.0 L/min.

A stationary three-stage Respicon impactor (Helmut Hund GmbH, Wetzlar, Germany) was utilized to obtain additional information about respirable, thoracic, extra-thoracic, and inhalable aerosol fractions. The Respicon was equipped with three PVC filters, each with a 5 µm pore size, and was connected to a Casella APEX 2 Pro air sampling pump, which operated at a controlled airflow rate of 3.11 L/min.

The airflow rates for all samplers were measured and recorded before and after each sampling session using a Bios Defender 510-M primary airflow meter (Mesa Laboratories, Lakewood, CO, USA).

Sampling procedure

A total of 146 participants were included in the sampling campaign. The sampling duration ranged from 310 to 510 min, with an average duration of 429 min. To account for day-to-day variability, the study included varying sampling durations: 96 participants were monitored for one day, 40 for two days, and 10 for three days.

Each participant was equipped with a backpack carrying both the GSP and IOM samplers mounted on

the right shoulder strap, ensuring both samplers were positioned within the worker's breathing zone throughout the sampling period.

Gravimetric analysis

Before and following sampling, all filters underwent a 24-hr conditioning period in a controlled environment maintained at 20 ± 1 °C and 40 ± 2% relative humidity. Post-sampling, the particulate mass collected on each filter was determined using a Sartorius MSA 6.6S microbalance (Sartorius AG, Göttingen, Germany). To eliminate static charge interference, filters were neutralized using a Polonium-210 α-emitter (StaticMaster, Nuclear Products Co., California, USA).

The mass limit of detection (LOD) for each sampler type was established by calculating three times the standard deviation of blank measurements obtained from six unexposed filters. This resulted in an LOD of 0.024 mg/filter for the GSP samplers and 0.025 mg/filter cassette for the IOM samplers. Aerosol concentrations were then calculated by dividing the measured particulate mass by the respective sampled air volumes.

The aerosol mass collected using the Respicon sampler and LODs were calculated as previously described by Skaugset et al. (Skaugset et al. 2013). The LODs for the collected mass, calculated as three times the standard deviation of six unexposed filters, were 0.007 mg for the respirable fraction, 0.009 mg for the thoracic fraction, and 0.011 mg for the inhalable fraction.

Filter extraction and soluble protein (SP) determination

After determining particulate mass, an optimized SP extraction method and modified bicinchoninic acid assay (BCA) procedure described previously by Darbakk et al. (2024) were employed to extract and determine SP from the filters.

Each filter was dissolved in a solution of phosphate-buffered saline (PBS) containing 0.5% Tween 20. Filters were sonicated for 5 min, followed by 1 hr of orbital shaking. At last, all filter extracts were centrifuged at 4,800 × *g* for 10 min. The filter extract was then analyzed using either the Pierce Enhanced BCA Protein Assay Kit (Thermo Fisher, Waltham, Massachusetts, USA) for protein concentrations between 5 and 250 µg/mL, or the Pierce Micro BCA Protein Assay Kit (Thermo Fisher) for SP concentrations between 2 and 40 µg/mL (Smith et al. 1985). All filter extracts were analyzed in triplicate.

The Micro BCA assay, with a detection limit of 2 µg protein/mL for a 96-well plate (Thermo Fisher), allowed for a minimum quantifiable protein amount of 6 µg/filter. The concentration limit of detection (cLOD) for SP collected with GSP and IOM was 4 µg/m^3 and 7 µg/m^3 at a sampling time of 429 min and an airflow rate of 3.5 L/min and 2.0 L/min, respectively.

Statistical analysis

Statistical analyses and data visualization were performed using R/RStudio version 4.4.1 (RC Team 2023) for descriptive statistics, Bland-Altman plots, and ratio calculations. The R packages rstatix were used for statistical analyses, and ggplot2 for graphical outputs (Kassambara 2023; Wickham 2016). The Shapiro-Wilk test indicated a non-normal distribution for both aerosol and SP concentrations ($p < 0.05$) (Shapiro and Wilk 1965), so a log transformation was applied before further analysis. After log-transformation, the data approached a normal distribution.

Bland-Altman plots were used to assess the agreement between the complete pairs of GSP and IOM samplers in measuring inhalable aerosol and only for samples > LOD for SP concentrations (Bland and Altman 1986). The mean ratio between complete pairs of GSP and IOM samplers and Pearson's correlation analysis were performed to explore the relationship between inhalable aerosol and SP concentrations. Pairs where either sample was below the analytical detection limit were excluded from the analysis. Additional analyses were performed after removing statistical outliers identified using Cook's distance test.

Mixed-effects Tobit regression models, performed in Stata 18 (StataCorp 2023), were used to assess the effects of air sampler type and production environment on both inhalable aerosol and SP concentrations, accounting for censored data. The analysis was performed on data with complete sampling pairs (GSP/IOM), and the participant ID was included as a random effect to account for variability between individuals. The following models were used:

$$\log\ \text{aerosol}\ (\text{mg/m}^3) = \text{air sampler} + \text{production type} + (1 \mid \text{ID}) + \varepsilon \quad (1)$$

$$\log\ \text{SP}\ (\mu\text{g/m}^3) = \log\ \text{mg/m}^3 + \text{air sampler} + \text{production type} + (1 \mid \text{ID}) + \varepsilon \quad (2)$$

where log mg/m^3 represents log-transformed inhalable aerosol concentrations, log µg/m^3 represents log-transformed SP concentrations, air sampler is a

categorical variable (GSP vs. IOM), production type is categorical (e.g., baked goods, coffee, spices, etc.), ID refers to the participant identifier (p001 to p146), and ε is the residual error.

In the linear regression analysis of inhalable aerosol (mg/m^3) and SP concentrations ($\mu g/m^3$) of GSP and IOM samplers across different product environments, values below LOD for SP concentrations were substituted with LOD/2.

Results

Exposure measurements

Personal exposure measurements

A total of 412 air samples were collected, with 13 samples excluded due to sampling errors. Of the remaining 399 samples, 202 were collected using IOM samplers and 197 using GSP samplers, resulting in 193 complete sampling pairs (386 samples).

Table 1 and Table S1 in the Supplementary material summarize the concentrations of inhalable aerosols and SP measured from complete GSP and IOM sampling pairs across different food production environments. Notably, the data revealed variations in measured concentrations depending on the sampler employed. Overall, median aerosol concentrations varied by production type, ranging from 0.2 mg/m^3 in snacks, nuts, and chips to 5.6 mg/m^3 in spread production. The highest 90th percentile concentration was observed in spice production (12 mg/m^3), while the lowest was found in snacks, nuts, and chips production (0.2 mg/m^3).

When comparing the two types of samplers overall, IOM samples exhibited a median aerosol concentration of 1.8 mg/m^3 (range: 0.04 to 16 mg/m^3), with a 90th percentile concentration of 6.4 mg/m^3. In contrast, GSP samples had a lower median concentration of 1.4 mg/m^3, with a range of 0.1 to 19 mg/m^3, and a 90th percentile concentration of 7.7 mg/m^3. An additional analysis revealed that inhalable aerosol concentrations (in mg/m^3) were generally higher for the IOM sampler across most percentiles, with the GSP and IOM lines intersecting around the 80th percentile (see Figure S1A in the Supplementary material). Wall deposits for the IOM sampler were also examined, showing values ranging from 10% to 30%. The highest wall deposits occurred in the production of snacks, nuts, and chips, while spread production had the lowest wall deposits (Table S2 in the Supplementary material).

Analysis of SP concentrations was conducted on 193 sampling pairs; however, during sampling preparation, eight sampling pairs from bakery operations were lost, resulting in 185 sampling pairs (370 samples) being analyzed for SP. Approximately 42% of IOM samples and 28% of GSP samples had SP concentrations below the limit of detection, resulting in 103 complete pairs above LOD. Median SP concentrations were 43 $\mu g/m^3$ for IOM samples (range: <cLOD to 1,300 $\mu g/m^3$; 90th percentile: 409 $\mu g/m^3$) and 48 $\mu g/m^3$ for GSP samples (range: <cLOD to 797 $\mu g/m^3$; 90th percentile: 442 $\mu g/m^3$).

Spread production showed the highest median SP concentrations, with 617 $\mu g/m^3$ for IOM samples and 426 $\mu g/m^3$ for GSP samples. This was followed by spice production, with a median of 254 $\mu g/m^3$ for IOM and 270 $\mu g/m^3$ for GSP. In contrast, the confectionery and chocolate production consistently yielded median SP concentrations below the limit of

Table 1. Concentrations of inhalable aerosols (mg/m^3) and soluble proteins (SP, $\mu g/m^3$) measured from complete IOM sampling pairs across various food production industries.

Production type	Inhalable aerosol (mg/m^3)	SP ($\mu g/m^3$)[a]
Baked goods		
N =	57	49 (9 <cLOD)
Median	2.4	107
Min	0.1	<cLOD
Max	14	764
Cake and baking ingredients		
N =	7	7 (5 <cLOD)
Median	2.6	<cLOD
Min	0.2	<cLOD
Max	6.3	408
Coffee		
N =	8	8 (4 <cLOD)
Median	0.6	29
Min	0.2	<cLOD
Max	6.2	609
Confectionery and chocolate		
N =	31	31 (25 <cLOD)
Median	1.3	<cLOD
Min	0.3	<cLOD
Max	4.8	49
Powder consumer products		
N =	59	59 (21 <cLOD)
Median	1.7	52
Min	0.1	<cLOD
Max	16	1340
Snacks, nuts and chips		
N =	15	15 (13 <cLOD)
Median	0.2	<cLOD
Min	0.04	<cLOD
Max	1.5	77
Spice		
N =	12	12
Median	4.0	254
Min	0.8	45
Max	13	1010
Spread		
N =	4	4
Median	5.6	617
Min	1.2	195
Max	8.4	747

[a]cLOD = 7 $\mu g/m^3$ at a sampling time of 429 min and an airflow rate of 2.0 liters/min for IOM.

detection. The highest 90th percentile concentrations were observed in the spice production (977 µg/m^3 for IOM samples) and spreads production (741 µg/m^3 for IOM samples). An additional analysis showed that SP concentrations (in µg/m^3) were higher for the GSP sampler from the 10th to the 40th percentiles, after which the IOM sampler showed higher concentrations from approximately the 50th percentile onwards (see Figure S1B in the Supplementary material).

Stationary measurements

Table 2 shows the distribution of median aerosol concentrations collected with the stationary Respicon sampler across various dry food production environments, categorized into respirable, thoracic, inhalable, and extra-thoracic aerosol fractions. The data indicated that spread production and confectionery and chocolate production had the highest median inhalable aerosol concentrations at 0.75 mg/m^3 and 0.68 mg/m^3, respectively. In contrast, coffee production had the lowest median inhalable concentration at 0.14 mg/m^3. The percentage of the inhalable fraction that was respirable or thoracic also varied across environments, with snacks, nuts, and chips, and spread production showing the highest percentages of the inhalable fraction that were thoracic (64% and 70%, respectively). The extra-thoracic fraction was highest for confectionery and chocolate production, with a concentration of 0.48 mg/m^3, representing 71% of the inhalable fraction. This was followed by bakery operations and the production of cake and baking ingredients, where the extra-thoracic fraction accounted for 60% of the inhalable fraction in both cases. Spread production and snacks, nuts, and chips exhibited the lowest percentages of the extra-thoracic fraction among all production types.

Comparison of inhalable aerosol and SP by sampler type

The agreement in sampled inhalable aerosol and SP concentrations between the GSP and IOM samplers was assessed using Bland-Altman analysis, with results shown in Figure 1.

The Bland-Altman plot (Panel A) illustrates the difference between inhalable aerosol concentrations measured by GSP and IOM samplers against the mean concentration of the two samplers. The Bland-Altman plot revealed a mean difference of −0.3 mg/m^3 between the aerosol concentrations measured by the GSP and IOM samplers, indicating a slight but minimal systematic bias. The limits of agreement were calculated at 3.2 mg/m^3 (upper limit) and −3.7 mg/m^3 (lower limit).

For SP concentrations (Panel B), the mean difference between the samplers was −32 µg/m^3, indicating a slight negative bias where the GSP sampler showed lower SP concentrations than the IOM sampler on average. The limits of agreement were 247 µg/m^3 (upper limit) and −311 µg/m^3 (lower limit).

Mixed-effect model analyses

Tables 3 and 4 present the outcomes of mixed-effects Tobit regression models assessing the impact of production type and choice of air sampler on log-transformed inhalable aerosol and SP concentrations from complete sampling pairs, respectively. Both models included participant variability as a random effect. Additionally, the impact of production type and inhalable aerosol concentration on SP concentrations was analyzed separately for each sampler type (see Tables S3 and S4 in the Supplementary material).

As seen in Table 3, there is a statistically significant positive association between log-transformed inhalable aerosol concentrations and the intercept ($p < 0.01$).

Table 2. Median aerosol concentrations (mg/m^3) across various food production types collected with Respicon sampler, showing respirable, thoracic, inhalable, and extra-thoracic particle sizes as a percentage of the inhalable fraction.

		Median aerosol (mg/m^3)				As % of inhalable fraction		
Production type	N	Respirable	Thoracic	Inhalable	Extra-thoracic	Respirable	Thoracic	Extra-thoracic
Baked goods	6	0.04	0.16	0.39	0.23	11	40	60
Coffee	2	0.03	0.07	0.14	0.08	22	47	53
Confectionery and chocolate	5	0.03	0.20	0.68	0.48	4.7	29	71
Powder consumer products	6	0.05	0.07	0.16	0.09	28	43	57
Snacks, nuts, and chips	2	0.17	0.26	0.40	0.14	42	64	36
Spread production	4	0.23	0.52	0.75	0.23	31	70	30
Cake and baking ingredients	3	0.05	0.08	0.19	0.11	26	40	60

In terms of mass, the respirable fraction is included within the thoracic fraction, and both the respirable and thoracic fractions are part of the inhalable fraction. The extra-thoracic fraction, in terms of mass, represents the portion of the inhalable particles that are not included in the thoracic fraction. The table also includes the number of samples (N) for each production type.
N = number of samples.
cLOD respirable = 0.005 mg/m^3 at a sampling time of 430 min.
cLOD thoracic = 0.007 mg/m^3 at a sampling time of 430 min.
cLOD inhalable = 0.008 mg/m^3 at a sampling time of 430 min.

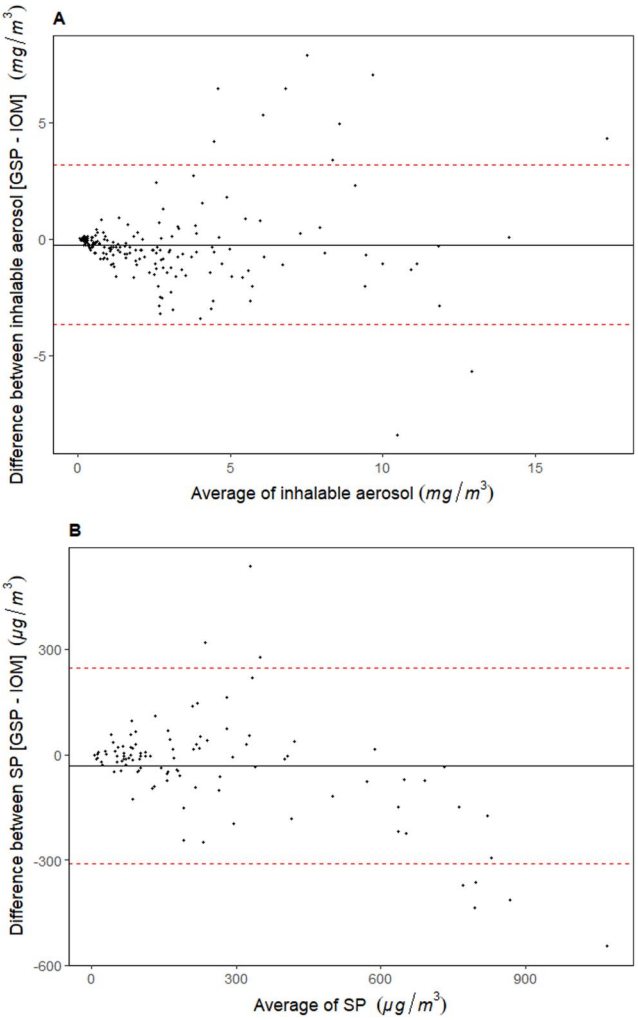

Figure 1. A Bland-Altman analysis was conducted between the two samplers, GSP and IOM. Panel A displays the agreement between 193 complete GSP and IOM sampling pairs on inhalable aerosol collection, while Panel B shows the agreement between 103 complete GSP and IOM sampling pairs on soluble protein (SP) collection (values < LOD not included). The solid black horizontal line represents the mean difference between measurements (where IOM measurements were subtracted from GSP measurements), while the red dashed lines indicate the upper and lower confidence intervals.

Table 3. Tobit mixed-effects model assessing the impact of air sampler type (GSP/IOM) and production on log-transformed inhalable aerosol concentrations of 193 complete sampling pairs.

	Model output		
Predictors	Coefficient	95% CI	*p*
(Intercept)	0.495	0.140–0.851	**<0.01**
Sampler: IOM	0.243	0.128–0.359	**<0.01**
Cake and baking ingredients	−0.530	−1.498–0.438	0.28
Coffee	−1.154	−2.117 – −0.191	**0.02**
Confectionery and chocolate	−0.647	−1.217–0.076	**0.03**
Powder consumer products	−0.349	−0.827–0.129	0.15
Snacks, nuts, and chips	−1.958	−2.664 – −1.125	**<0.01**
Spice	0.692	−0.426–1.811	0.23
Spread	0.630	−0.930–2.190	0.43
Var(intercept)			1.119
Var(e. log aerosol, mg/m^3)			0.332
Wald chi^2 (8)			56.65
Log likelihood			−493.74
Observations			386

Production of baked goods and the GSP inhalable air sampler were set as references. Statistically significant differences are marked in bold ($p < 0.05$).

Table 4. Tobit mixed-effects regression model assessing the impact of air sampler type (GSP/IOM) and production on log-transformed soluble protein (SP) concentrations of 185 complete sampling pairs.

	Model output		
Predictors	Coefficient	95% CI	*p*
(Intercept)	3.490	3.042–3.938	**<0.01**
Log aerosol (mg/m^3)	1.051	0.891–1.210	**<0.01**
Sampler: IOM	−0.525	−0.754 – −0.296	**<0.01**
Cake and baking ingredients	−0.840	−2.022–0.342	0.16
Coffee	0.632	−0.485–1.750	0.27
Confectionery and chocolate	−2.625	−3.338 – −1.911	**<0.01**
Powder consumer products	−0.025	−0.594–0.544	0.93
Snacks, nuts, and chips	−1.871	−2.881 – −0.861	**<0.01**
Spice	0.990	−0.231–2.211	0.11
Spread	1.466	−0.248–3.181	0.09
Var(intercept)			1.184
Var(e. log SP, µg/m^3)			0.98
Wald chi^2 (8)			310.94
Log likelihood			−501.60
Observations			370

Production of baked goods and the GSP inhalable air sampler were set as references. Statistically significant differences are marked in bold ($p < 0.05$). 95% CI = 95% confidence intervals.

The IOM sampler showed, when all sample pairs were included, statistically significantly higher inhalable aerosol concentrations compared to the GSP sampler ($p < 0.01$). However, when analyzing only the aerosol collected onto the filter for IOM, no statistically significant difference was observed between IOM and GSP in the model (median IOM inhalable aerosol for filter mass only = 1.5 mg/m^3, $p = 0.92$; data not shown). Among production types, coffee ($p = 0.02$), confectionery and chocolate ($p = 0.03$), and snacks, nuts, and chips production ($p < 0.01$) showed significantly lower inhalable aerosol concentrations compared to the bakery operation reference. Other production types, including powder consumer products ($p = 0.15$) and cake and baking ingredients ($p = 0.28$), did not show statistically significant reductions in inhalable aerosol concentrations. Similarly, spice production ($p = 0.23$) and spread production ($p = 0.43$) did not show a statistically significant increase in inhalable aerosol concentrations. The model indicated that a significant amount of variability in log-transformed inhalable aerosol concentrations was attributable to differences between participants, as reflected by the variance of the intercept (1.119). The residual variance was estimated at 0.332, indicating

the unexplained variability in aerosol concentrations not accounted for by the model predictors.

In Table 4, a significant positive association was observed between the log-transformed inhalable aerosol concentration and SP concentration ($p < 0.01$), indicating an increase in SP concentrations with higher aerosol concentrations. The IOM air sampler, when compared to GSP, showed significantly lower SP concentrations when all sample pairs were included ($p = 0.02$). Production type also had a notable impact on SP concentrations. Confectionery and chocolate production showed significantly lower SP concentrations compared to the bakery operations reference ($p < 0.01$). Similarly, snacks, nuts, and chips production had significantly lower protein concentrations ($p < 0.01$). Spice production showed a positive, though not statistically significant, association with SP concentrations ($p = 0.11$). Other production environments, such as coffee ($p = 0.27$), powder consumer products ($p = 0.93$), spread ($p = 0.09$ and cake and baking ingredients ($p = 0.16$), did not show statistically significant effects. The random effect of the participant's intercept had a variance of 1.184, reflecting variability between participants. The residual variance for the log-transformed inhalable TSP concentrations was 0.98. The model's fit statistics show a Wald chi-squared of 310.94, with a log likelihood of −501.60, based on 370 observations.

Correlation between aerosol and SP by production type

A linear regression analysis of the log-transformed inhalable aerosol and SP concentrations for both GSP and IOM samplers was tested overall. A positive linear correlation was found between inhalable aerosol and SP concentrations for both samplers. For the GSP sampler, the coefficient of determination (R^2) was 0.45, indicating that 45% of the variability in SP concentration can be explained by the aerosol concentration. The IOM sampler showed a slightly higher R^2 value of 0.48, meaning that 48% of the variability in SP concentration is accounted for by the aerosol concentration. A linear regression analysis was conducted for both the GSP and IOM samples across each production type, with results displayed in Figure S2 in the Supplementary materials, highlighting variability in the observed correlations.

Furthermore, a comparative analysis of inhalable aerosol and SP concentrations measured using IOM and GSP samplers across various food production settings was performed (Table 5). For inhalable aerosols, the results showed that the GSP generally collected on average 17% (range 6–39%) less aerosol than the IOM, with mean GSP/IOM ratios below 1 in most production environments. In bakery operations, for example, the mean ratio was 0.89, with a strong correlation coefficient ($r = 0.83$), indicating a consistent relationship between the two samplers. Similarly, in the production of powder consumer products, the GSP/IOM ratio was 0.94, with a correlation of 0.84. The snacks, nuts, and chips production showed that the GSP collected more aerosol compared to IOM, as indicated by a ratio of 1.32 and a correlation of 0.67. After statistically significant outliers were removed using Cook's distance test, the mean ratios for the different production environments shifted as follows: the mean ratio for bakery operations was 0.78, with a confidence interval of 0.70 to 0.86 and a correlation coefficient of 0.94. For powder consumer products production, the mean ratio was 0.90, with a confidence interval of 0.76 to 1.04 and a correlation coefficient of 0.87. Similarly, snacks, nuts, and chips production had a mean ratio of 1.00, with a confidence interval of 0.75 to 1.26 and a correlation coefficient of 0.89, while spice production showed a mean ratio of 0.82, with a confidence interval of 0.60 to 1.04 and a correlation coefficient of 0.94.

In terms of SP measurements, the IOM sampler measured SP concentrations that were 3 to 28% higher than the GSP for bakery operations, confectionery and chocolate, snacks, nuts, and snacks and spread production, with similar correlation coefficients ranging between 0.84 and 1.00. Conversely, in coffee, powder consumer products, spices, and cake and baking ingredients production, the GSP sampler measured slightly higher SP concentrations (4–7%) compared to the IOM sampler. The correlation coefficients for these production environments were similarly high, ranging from 0.86 to 0.99. When statistically significant outliers were removed using Cook's distance test, the mean ratios for powder consumer products and spice production shifted to 1.25 and 0.95, respectively. The mean ratio confidence intervals for these production environments were 0.86 to 1.64 for powder consumer products and 0.72 to 1.18 for spice production, with corresponding correlation coefficients of 0.92 and 0.96.

Discussion

This study investigated the performance of the GSP and IOM samplers in various food production environments, focusing on their ability to measure

Table 5. Comparative analysis of inhalable aerosol and soluble protein (SP) concentrations measured by complete IOM and GSP sampling pairs across various food production settings, including the average ratio between GSP and IOM, and the Pearson correlation coefficients (r) for each production environment.

	Inhalable aerosol (mg/m^3)				SP (μg/m^3)			
Production	N =	Mean ratio (GSP/IOM)	Mean ratio 95% CI	r (GSP/IOM)	N =	Mean ratio (GSP/IOM)	Mean ratio 95% CI	r (GSP/IOM)
Baked goods	57	0.89	0.75–1.03	0.83	39	0.97	0.82–1.12	0.84
Coffee	8	0.88	0.49–1.27	0.98	4	1.07	0.48–1.66	0.99
Confectionery and chocolate	31	0.85	0.60–1.09	0.83	3	0.75	−0.36–1.87	0.86
Powder consumer products	59	0.94	0.80–1.09	0.84	37	1.54	0.93–2.16	0.86
Snacks, nuts, and chips	15	1.32	0.60–2.03	0.67	2	0.96	−0.46–2.38	1.00
Spice	12	0.87	0.66–1.09	0.90	12	1.04	0.71–1.36	0.89
Spread products	4	0.72	0.40–1.05	0.95	4	0.72	0.51–0.92	0.96
Cake and baking ingredients	7	0.61	0.36–0.86	0.89	2	1.07	−0.27–2.42	1.00

N = presents the total number of sample pairs.
CI = confidence intervals.
r = Pearson's correlation coefficient.
Samples below the detection limit for SP (4 μg/m^3) are not included.

inhalable aerosol and SP concentrations. In occupational hygiene, a certain magnitude of difference between different air sampling methods is usually accepted. For instance, the National Institute of Occupational Safety and Health (NIOSH) has an accuracy criterion of ±25%, wherein at least 95% of measurements must fall within 25% of the true (or reference) value in laboratory studies (Eller et al. 1995). In field studies, a higher difference between air sampling methods than the NIOSH criterion may be acceptable, as field studies can have highly variable environmental conditions (Bartley et al. 2007; Lee et al. 2011).

The performance of both samplers was influenced by the particle size distributions, leading to variations in aerosol and SP concentration mean ratios between the GSP and IOM samplers in different settings (Table 5). In bakery operations and confectionery production, random stationary measurements showed that 60–71% of the inhalable fraction consisted of extra-thoracic particles (Table 2). This finding aligns with a study reporting 85% of the inhalable fraction in bakery environments being extra-thoracic (Kirkeleit et al. 2017). Consistent with these results, the IOM sampler measured higher median inhalable aerosol concentrations compared to the GSP (Table 1 and Table S1 in Supplementary material). These observations align with wind tunnel studies (Kenny et al. 1997, 1999), which demonstrated that the GSP had 8–34% lower sampling efficiency for particles with a d_{ae} above 40 μm compared to the IOM. In contrast, the snacks, nuts, and chips production environment, where random stationary measurements found that 42% and 64% of the inhalable fraction consisted of respirable and thoracic particles, respectively, showed a higher mean ratio for aerosol concentrations for the GSP sampler compared to the IOM sampler (Table 5). These findings are consistent with previous wind tunnel studies, where the GSP had a slightly higher (6%) sampling efficiency than the IOM sampler for particles < 20 μm (Kenny et al. 1999). Furthermore, Lee et al. reported a geometric mean ratio of 0.70 and a Pearson correlation of 0.91 between the GSP and IOM samplers, which are consistent with this study's ratio and correlations (Lee et al. 2011).

In environments dominated by larger, extra-thoracic particles (e.g., bakery operations), the IOM's larger inlet may overestimate exposure by capturing particles influenced by airflow patterns (Aizenberg et al. 2000). This is particularly relevant in bakery settings, where variations in air currents may result in inconsistent large-particle capture, contributing to discrepancies between the samplers. The IOM's larger inlet also increases the likelihood of capturing projectiles or droplets, further causing an oversampling of the aerosol exposure estimate. In contrast, the GSP's smaller inlet may mitigate this risk, reducing the potential for overestimation of the inhalable aerosol (Aizenberg et al. 2000). In addition, the differences observed between the GSP and IOM sampler could be due to aerosol particles larger than 100 μm, which is sampled more efficiently by the IOM (Aizenberg et al. 2001).

Another factor that might contribute to discrepancies between samplers is the handling of wall-deposited material. The IOM includes wall deposits in its aerosol measurements, which can result in higher overall concentrations. However, when analyzing only the filter mass without the wall deposits, no statistically significant difference was observed.

Previous studies have reported median wall deposits of 3 to 19%, with maximum values ranging from 3 to 69% (Harper 2020). In this study, IOM wall deposits ranged from 10 to 30%, with snacks, nuts, and

chips production showing the highest values, while spread production had the lowest (Table S1 in Supplementary material). The GSP, analyzing only filter deposits, tended to sample lower median aerosol concentrations in all the measured environments. It is also worth noting that the greatest contribution to wall deposits in any sampler is often due to particle bounce from the filter, as demonstrated by Li et al. (2000).

However, in this study, wall-deposited material was excluded from the SP analysis to reduce the total volume used for extraction. Despite this, the IOM still showed consistently higher median SP concentrations in bakery operations, spread and confectionery, and chocolate production environments than the GSP (Table 2). However, when the median SP fraction was compared between the samplers in bakeries, the values were nearly identical ($\approx$ 0.04 for GSP and IOM in bakery operations, and $\approx$ 0.11 for GSP and IOM in spread production). This could be due to extra-thoracic particles having a lower surface-to-volume ratio relative to the thoracic particles, which limits the binding of surface-associated proteins and their dissolution during extraction (Vishwanathan et al. 2011). Consequently, while the IOM samples higher absolute SP concentrations, it doesn't sample a proportionally higher fraction of SP, indicating that both samplers performed similarly for sampling SP concentrations in these environments.

In environments dominated by respirable particles, such as coffee production, powder consumer products, spices, and cake and baking ingredients, the GSP showed slightly higher SP concentrations than the IOM, despite the IOM generally sampling higher total aerosol concentrations (Table 3). This can be attributed to the GSP's slightly higher sampling efficiency for smaller, respirable particles, which aligns with wind tunnel data showing the GSP sampling efficiency was higher than the IOM sampling efficiency for particles with $d_{ae} < 20\,\mu m$ (Kenny et al. 1999). The greater surface area-to-volume ratio of smaller particles enhances protein accessibility and dissolution (Hinds 1982; Vishwanathan et al. 2011). Furthermore, the differences observed in SP concentrations between the GSP and IOM might be due to differences in the sampling efficiency of particle sizes of the selected sampler and variations in SP extraction efficiencies.

The Tobit mixed-effects models (Tables 3 and 4 and Tables S3 and S4 in Supplementary material) strengthen these observations, showing significant positive associations between inhalable aerosol concentrations and SP concentrations for both samplers. These models highlight the impact of production type on SP concentrations, particularly the reductions observed in confectionery and chocolate production environments for both the IOM and GSP samplers ($p < 0.01$). For the IOM sampler, a significant reduction was also observed in cake and baking ingredients ($p = 0.05$). The IOM's response was more pronounced in environments like bakery operations and spread production, where extra-thoracic particles dominate. Meanwhile, the GSP was more effective in collecting aerosols in environments dominated by respirable particles, such as snacks, nuts, and chips production ($p = 0.002$).

The Bland-Altman analysis further indicated systematic differences between the GSP and IOM samplers (see Figure 1). For inhalable aerosol concentrations, the GSP generally measured slightly lower concentrations than the IOM, as indicated by the mean difference of $-0.3\,mg/m^3$. This suggests a minimal bias, though the relatively wide limits of agreement (-3.7 to $3.2\,mg/m^3$) indicate potential variability in individual measurements. Similarly, the analysis of SP concentrations revealed a mean difference of $-32\,\mu g/m^3$, with the GSP tending to sample lower concentrations than the IOM. The broader limits of agreement for SP concentrations (-311 to $247\,\mu g/m^3$) suggest that the two samplers may diverge more when measuring SP in complex aerosol environments.

Limitations

Several limitations must be acknowledged. The focus on the food industry may limit the generalizability of the findings to other occupational settings with different aerosol characteristics. Additionally, small sample sizes for certain production types may reduce the statistical power of the study, requiring cautious interpretation of the results. In settings with a high number of samples below the limit of detection for SP concentrations, the mean ratio between the GSP and IOM samplers may be affected, potentially leading to less reliable comparisons. Another limitation concerning the SP concentrations is that only the filter was analyzed for SP concentration in the IOM sampler, leaving the potential for differences in particle characteristics, such as size or SP concentration, between those deposited on the filter and those on the walls, which could influence the overall measurement. Finally, the placement of the stationary Respicon sampler in factory environments was sometimes suboptimal, which could impact the representativeness of the data. Additionally, these stationary samples were

random measurements, which might not fully represent the personal samples, as there might be differences in particle size distribution within and between production environments and between days.

Conclusion

This study has investigated the comparability between the GSP and IOM samplers across various food production environments and identified statistically significant differences in aerosol and protein concentrations between the two samplers. The results showed that the IOM sampler sampled higher aerosol and SP concentrations than the GSP sampler across various production environments. The differences in aerosol concentrations may be attributed to wall deposition, as well as the design of the IOM sampler, which features a larger inlet that increases susceptibility to trajectories and splashing. The observed differences in SP concentrations between the GSP and IOM samplers could be attributed to variations in particle size sampling efficiencies and discrepancies in SP extraction efficiencies. However, the magnitude of these differences in aerosol and SP concentrations between samplers was acceptable from an occupational hygiene practitioner's point of view. In cases where specific analyses of SP or other relevant bioaerosol components of the collected aerosol samples will be performed, the increased aerosol mass collected by the GSP sampler, due to the higher air sampling flow rate, could be beneficiary.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethics declarations

All participants have given informed written consent to participate in the study, and participation was voluntary. According to the Norwegian national rules, an ethical approval was not necessary for the data obtained in this study. However, the Norwegian Agency for Shared Services in Education and Research has assessed the planned processing of personal data and found it in compliance with requirements in the data protection legislation (reference number 662161).

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

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