

# Exposure assessment of nanotitanium oxide powder handling using real-time size-selective particle number concentration measurements and X-ray fluorescence spectrometry —The possibility of exposure to nonagglomerated nanomaterials during the handling of nanomaterial fine powders—

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**Abstract:** In this study, airborne particles were collected using filters, and the particle number concentrations were measured in two nanotitanium dioxide (nanoTiO<sub>2</sub>)-manufacturing plants. Real-time particle size measurements were performed using both optical and scanning mobility particle sizer and X-ray fluorescence spectrometry (XRF). The respirable particles collected using filters were used to analyze Ti concentrations in the workplace air of two factories engaged in nanoTiO<sub>2</sub> powder bagging processes. The XRF analysis revealed sufficient sensitivity to measure 0.03 mg/m<sup>3</sup>, which is 1/10 the concentration of the recommended occupational exposure limit of nanoTiO<sub>2</sub> in both stationary sampling and personal exposure sampling settings. In a factory where outside air was directly introduced, micron-sized aggregated particles were generated because of factory operations; however, nanosized and submicron-sized particles were not observed owing to high background concentrations of incidental nanoparticles. Alternatively, in another factory where particles from the outside air were removed using a high-efficiency particulate air filter, work-related nanoparticles were released. The findings of this study suggest that in nanoparticle powder handling processes, a nanoparticle exposure risk exists in the form of nonagglomerated state in nanoparticle powder handling processes.

**Key words:** TiO<sub>2</sub>, Nonagglomerated nanoparticles, Nanomaterial, Industrial hygiene, Work environment, Nanotitanium dioxide, Exposure assessment

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## Introduction

Over the last two decades, risks to workers from nanomaterial exposure have become an important topic of interest in the field of occupational health<sup>1–9</sup>. These risks come from two factors. First, nanomaterials constitute a new type of material introduced into the workplace, and their health risks have hitherto been unknown<sup>3, 8, 9</sup>. Second, the negative health effects of small particles with sizes of <100 nm in atmospheric air, known as incidental nanoparticles, have already been established in epidemiological studies<sup>10–13</sup>.

Exposure surveys targeting workers handling engineered nanomaterials have been conducted in response to concerns about the health risks posed by engineered nanoparticles. For instance, we conducted exposure surveys in factories handling carbon nanotubes<sup>14, 15</sup> and carbon black<sup>15</sup>. Similar to carbon-based nanomaterials, it is important to evaluate workers' exposure to nanotitanium dioxide (nanoTiO<sub>2</sub>)<sup>1, 2, 16–19</sup>.

TiO<sub>2</sub> is used in paints, varnishes, lacquer, paper, plastics, ceramics, printing ink, and fundamental industrial materials<sup>1, 2</sup>. NanoTiO<sub>2</sub> particles, with diameters of <0.1 μm, are used to improve optical and chemical properties such as ultraviolet light absorption and catalyst photochemical efficiency. To quantify exposure to nanomaterials, we used a combination of particle number and size measurements, as well as chemical analysis. Measurements of particle number and size provide real-time exposure data related to workers' activities. However, from our experiences<sup>14, 15</sup>, measuring the changes in the nanosized particle concentration with respect to nanomaterial handling has been difficult owing to the high background concentration of incidental nanoparticles. Based on mass concentration evaluations, most industrial nanomaterials are found in the workplace as submicron-sized aggregated particles, with TiO<sub>2</sub> being no exception. Some influential researchers believe that these toxic responses attributed to engineered nanoTiO<sub>2</sub> particles<sup>8, 20, 21</sup> are not correlated with the mass-based concentration but the total surface area. The US National Institute for Occupational Safety and Health (NIOSH)<sup>20</sup> and the Japan Society for Occupational Health (JSOH)<sup>21</sup> have published a recommended exposure limit (REL) and occupational exposure limit (OEL) of 0.3 mg/m<sup>3</sup> for nanoTiO<sub>2</sub> particles. This viewpoint is solely on mass-based concentrations as it has not been accepted and is difficult to confirm due to constraints in measurement technology. However, we assert that it is necessary to establish whether industrial nanomaterials are exposed as engineered

nanoparticles because the effects of incidental nanoparticles on health have also been reported<sup>10–13</sup>, and it remains unclear whether agglomerated or nonagglomerated (single) particles carry the same hazards<sup>3, 8, 9</sup>. However, quantifying nanosized particles and agglomerates from nanomaterials is difficult. It is essential to assess the exposure to nanosized particles in order to take effective health protection measures for workers because even the same primary particle sizes may have different toxicities if they have various agglomerate sizes<sup>22</sup>. As this question has yet to be clearly answered, knowing whether workers are exposed to nonagglomerated nanosized particles remains an important topic in the field of occupational health.

For investigating exposure to nanoTiO<sub>2</sub>, we used X-ray fluorescence spectrometry (XRF) as the most suitable chemical analysis method, combined with particle size measurements. The XRF measurement has been adopted as the official method by the US Environmental Protection Agency (EPA)<sup>23</sup> and the Ministry of the Environment of Japan<sup>24</sup> as an analytical method for detecting trace metal containing particles in the ambient atmosphere. These protocols of XRF offer sufficient precision<sup>23, 24</sup> to be viable for the measurement of nanoTiO<sub>2</sub> in the workplace at the 1/10 concentration recommended as the OEL<sup>20, 21</sup>. XRF also has an advantage over conventional metal analysis methods, such as atomic absorption spectrometry<sup>25</sup>, inductively coupled optical emission spectrometry, and inductively coupled mass spectrometry. These methods require sample digestion before introducing into the analytical devices. Such wet chemical methods for analyzing the TiO<sub>2</sub> concentration entail the decomposition of concentrated sulfuric acid. However, numerous industrial nanoTiO<sub>2</sub> applications feature hydrophobic surface treatments, making the decomposition of sulfuric acid difficult. XRF can be employed to assess solid samples and avoid the issue of acid decomposition<sup>23, 24</sup>.

The Ministry of Health, Labour and Welfare (MHLW) and the Japan Industrial Safety and Health Association (JISHA) provided us with the opportunity to measure particle release during the nano-TiO<sub>2</sub> powder bagging process in two nano-TiO<sub>2</sub>-manufacturing plants: one that was conventional plant and another where the air-derived background particles were actively removed. Based on our field survey, we note that the presence of some nonagglomerated nanoparticles comprising the nanomaterials. In this study, we highlight the exposure risks of nanoparticles to workers who are handling nanomaterials in their workplaces. We also demonstrate the use of XRF analyses of TiO<sub>2</sub> for evaluating the occupational exposure risk of nanoTiO<sub>2</sub>.

**Table 1. Parameters of real-time aerosol measurements**

Device	Air flow rate L/min	Sampling rate #/sec	Number of channels of particle sizes	Particle size ranges/nm
SMPS NanoScan 3910	0.25	60	13	10–13.3, 13.3–17.8, 17.8–23.7, 23.7–31.6, 31.6–42.2, 42.2–56.2, 56.2–75.0, 75.0–100.0, 100.0–133.4, 133.4–177.8, 177.8–237.1, 237.1–316.2, 316.2–420†
OPS 3330	1.0	15	16	300–374, 374–465, 465–579, 579–721, 721– 897, 897–1117, 1117–1391, 1391–1732, 1732–2156, 2156–2685, 2685–3343, 3343– 4162, 4162–5182, 5182–6451, 6451–8031, 8031–10000‡

† Mobility diameters: the ratio of the lower point of each particle size range was ca. 1.3.

‡ Optical diameters: the ratio of the lower point of each particle size range was ca. 1.25

## Materials and Methods

We conducted a field survey in two nanoTiO<sub>2</sub>-manufacturing factories, hereinafter referred to as factory A (FA) and factory B (FB). These two factories belong to the same chemical company in Japan. During the bagging process of rutile nano-TiO<sub>2</sub> powder, filtration was employed to conduct size-selective particle number concentration measurements and airborne respirable particle collection assessments. The TiO<sub>2</sub> concentration in the filtered airborne dust samples was then analyzed in a laboratory using XRF.

### Sample collection devices and analytical instrument

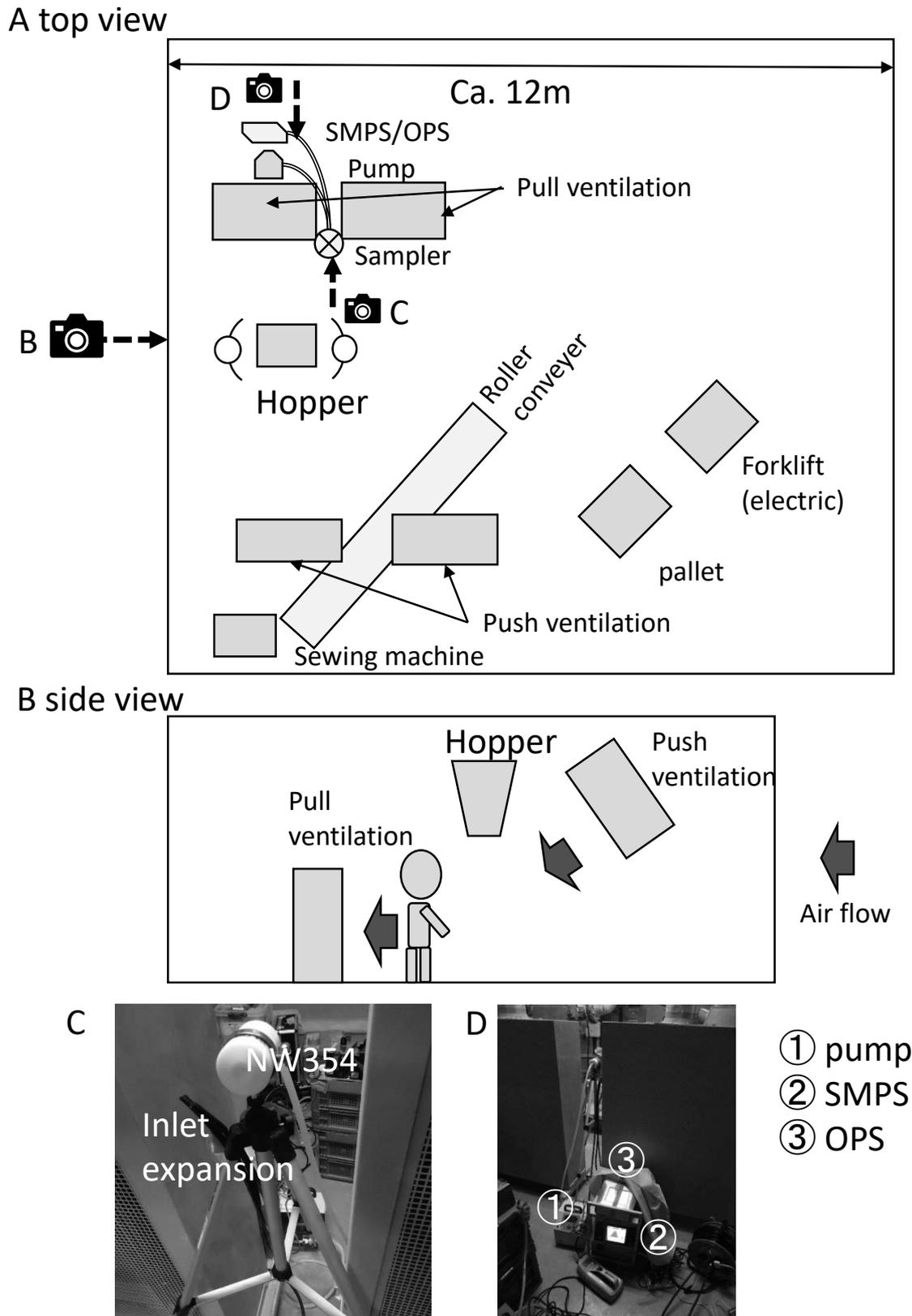
Size-selective particle number concentrations were measured using a portable scanning mobility particle sizer (SMPS: NanoScan 3910 TSI Inc., Shoreview, MN, USA) and an optical particle sizer (OPS: TSI 3330, TSI Inc.). The observed particle sizes were in the range of 10–400 and 300–1,000 nm using SMPS and OPS, respectively. Their operating parameters are presented in Table 1. All particles were assumed to be spherical, and their densities were equivalent to the bulk TiO<sub>2</sub> density (4.9 g/cm<sup>3</sup>) to convert the number concentrations into mass concentrations. Airborne particles were collected using polyvinyl chloride (PVC) membrane filters (GLA 5000, Pall, USA) by employing an NW354 sampler (Sibata Scientific Technology, Souka, Saitama, Japan) equipped with an LV-40 sampling pump (Sibata Scientific Technology). The NW354 sampler is an impactor-based, size-selective, low-volume air sampler, showing a calibration curve corresponding to the respirable particles defined in ISO7708: 1995<sup>26</sup>). The sampling air flow rate was 20 l/min, and the diameter of the

PVC membrane filter was 35 mm. Electroconductive silicone tubing was used to extend the sampling inlets in SMPS and OPS near the inlet of the NW354 sampler. The heights of the sampling locations were ~1.2 and ~2 m away from the hoppers, respectively. Fig. 1 presents the installation of one of the sampling devices. Sampled PVC membrane filters were analyzed using an EDXL-300 energy-dispersive XRF spectrometer (Rigaku, Akishima, Tokyo, Japan). XRF analysis was conducted using the absolute calibration method. Moreover, the calibration curve made with the standard series samples were prepared as follows: the rutile TiO<sub>2</sub> reagent (Fujifilm Wako Pure Chemical, Osaka, Japan) was suspended in pure water and spiked onto the designed filter media for liquid sample XRF analysis (UltraCarry light®, Rigaku), with TiO<sub>2</sub> masses of 0, 10, 25, 50, 100, and 250 µg in the filters.

### Details of the field for sample collection and measurement

Particle concentrations were measured, and airborne particles were collected during the bagging process of three types of hydrophobic-treated rutile nanoTiO<sub>2</sub>, of which two were from FA and the other from FB.

FA synthesized TiO<sub>2</sub> using the sulfuric acid method and had surface treatment facilities, where hydrophobic-treated TiO<sub>2</sub> products were fabricated. We measured the particle concentration and collected particles in two bagging rooms of FA-a and FA-b. The bagging process in both rooms entailed a gravity-driven powder falling into paper bags, with a local exhaust ventilation (LEV) system and combined hoppers in operation. Workers fed TiO<sub>2</sub> powder from the hopper into paper bags whose tops were open. Following powder filling, the worker (or another worker) adjusted the



**Fig. 1.** Layout of bagging tasks and measurement and sampling location in FA-a and photographs of sampler and particle number concentration measurement devices. A: top and B: side views of the layout of the workers and factory devices and ventilation. C: photograph of samplers. D: photograph of sampling pump and particle size and number measurement devices.

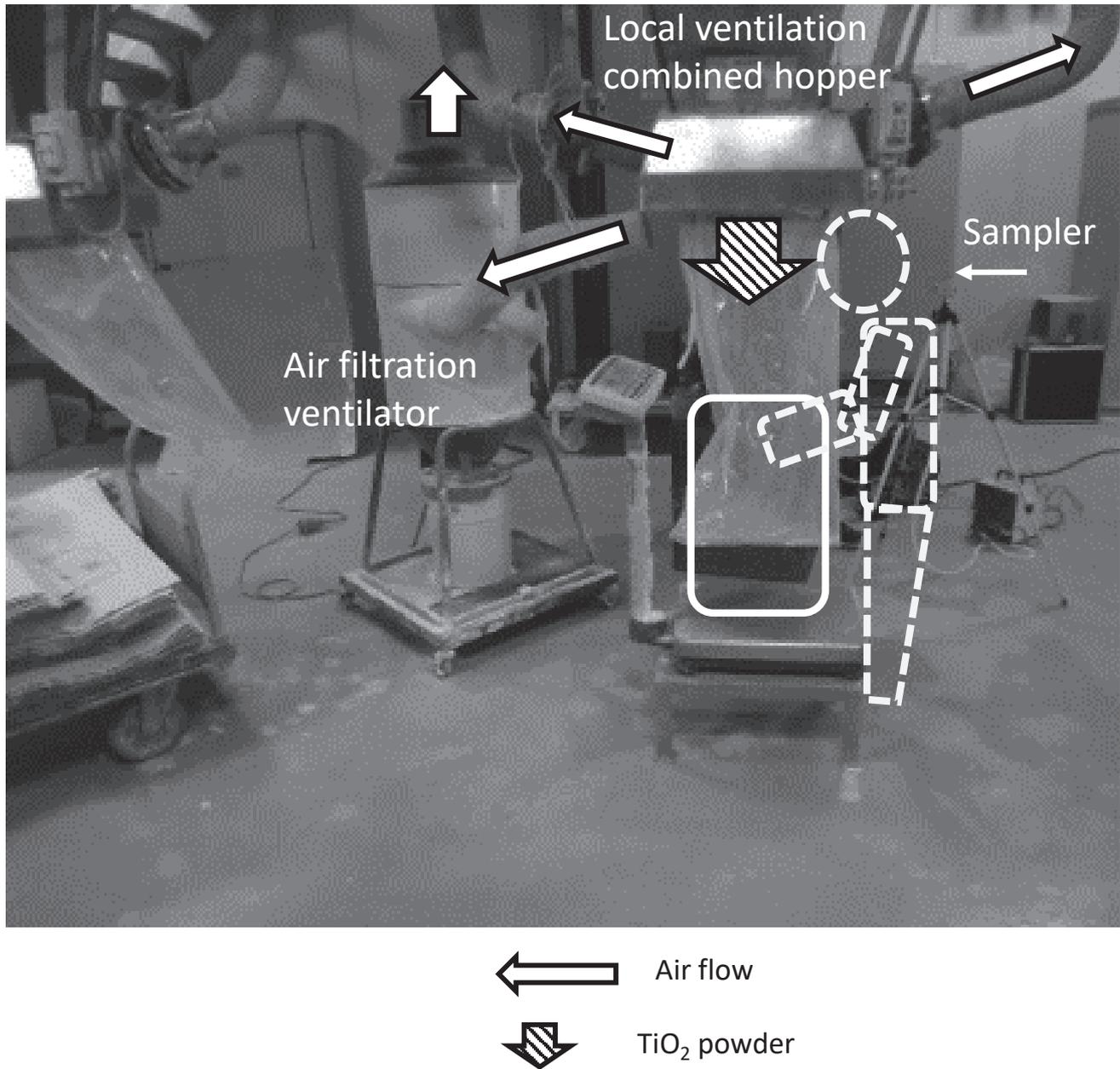


Fig. 2. Photograph of bagging task layouts in FA-b.

weight of  $\text{TiO}_2$  using hand ladles. Finally, the top of the bags was stitched using a sewing machine and stacked on pallets for shipment. Fig. 1 and 2 present the sampling process in FA-a and FA-b, respectively. The LEV system in the FA-a bagging room differed from that in the FA-b bagging room, comprising a push-pull type. The alignment of the push-pull ventilation system in FA-a is presented in Fig. 1B. The air for ventilation in the LEV system in FA was directly drawn from the ambient atmosphere without performing further filtration of atmospheric particulate matter.

The other factory, FB, had some facilities for the surface

treatment of fine particles for synthesizing ingredients for cosmetics. To avoid ambient-pollutant contamination and ensure the grade of the cosmetics, high-efficiency particulate air (HEPA)-filtered air was introduced through the ventilation systems. The bagging process was performed, with the related instrument and LEV systems in operation, in a clean room, which was continually supplied with the HEPA-filtered air. There were two ventilators and vibrating sieve-combined hoppers in the bagging room. Following filling and weight adjustments, the powdered product was placed in a plastic bag, and the bag was compressed in a

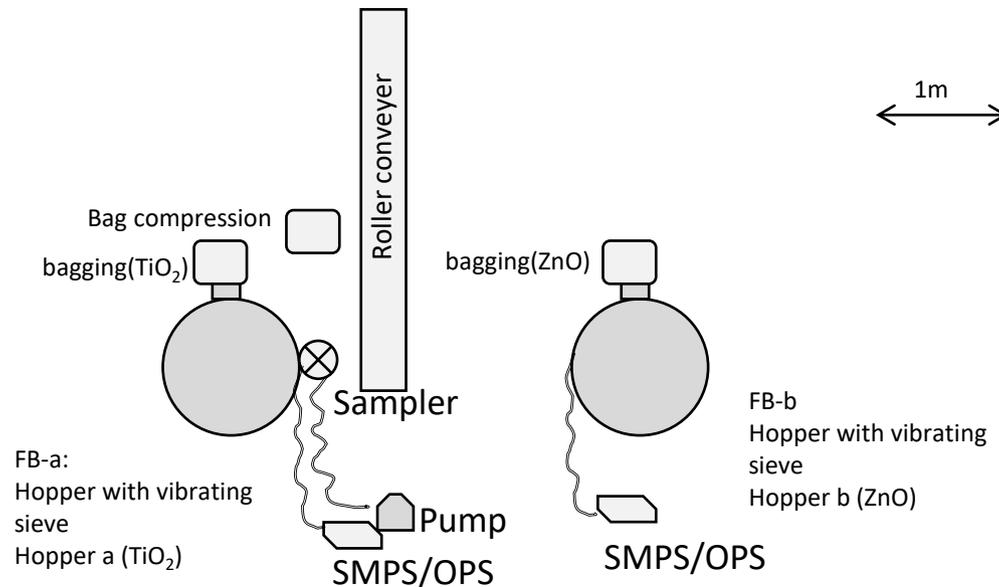


Fig. 3. Layout of bagging tasks and measurement and sampling location is FB.

small, ventilated box to decrease the volume. Finally, the bag was closed using a rubber ring and individually placed in a cardboard box. On the day when our measurements were conducted, two bagging operations were performed in sequence. First, nanoTiO<sub>2</sub> was bagged in one of the hoppers (FB-a) and nanoZnO was bagged in another hopper (FB-b). The two bagging operations were performed alternatively by the same team of workers. Two sets of SMPS and OPS were located near both hoppers, and the NW354 sampler was located near FB-a, shown in Fig. 3.

## Results

### *TiO<sub>2</sub> concentrations in the workplaces*

Fig. 4 presents filters with sampled particles on the surface. The color of the filters with sampled particles in FA was a darker gray than that in FB. This indicates that fewer particles are originating from the background in FB than in FA. The color of the filter face could be a qualitative index of particle concentrations from the outside air, as the outside air contains numerous colored particles derived from black soot or other combustion origin particles<sup>15</sup>.

The TiO<sub>2</sub> content in the sampled particles was measured via XRF analysis and converted to the particle number concentration, which was measured using OPS; the results are presented in Table 2. In FA, the particle concentration of TiO<sub>2</sub> was not obtained quantitatively due to the high background concentrations. Therefore, Table 2 presents the estimated values obtained using OPS in FB only. The order of

the TiO<sub>2</sub> concentration in the three sampled locations, namely, FA-a, FA-b, and FB, was almost the same. Alternatively, in FB, the order of the TiO<sub>2</sub> concentration obtained using XRF analysis differed from that estimated using the optical counting method.

### *Time course studies of the size distribution of particles in workplaces*

Fig. 5, 6, and 7 present the contour maps and particle number concentrations of classified size ranges, showing the time course of the particle size distribution in FA-a, FA-b, and FB, respectively. Horizontal black bands (count 0) can be observed in the center of all contour maps. Occasionally, a similar zero band was observed using the NanoScan, which was attributed to a technical error because the particle size was close to the upper limit of the particle size range of the device. Note that this error did not affect the results of our measurements.

With respect to the operation performed in FA, submicron-sized and nanosized particles were detected using SMPS and OPS; however, no relationship was observed between changes in airborne concentrations and bagging tasks with/without the push-pull ventilation system, which are shown in Fig. 5 and Fig. 6, respectively. Fig. 5 depicts the data acquired in FA-a with the push-pull ventilation system. The background concentrations of particles <100 nm in B1 and B2 (backgrounds) were generally higher than those in A1 and A2 (near the bagging task). The nanoparticle concentrations in A1 and A2 were slightly lower than

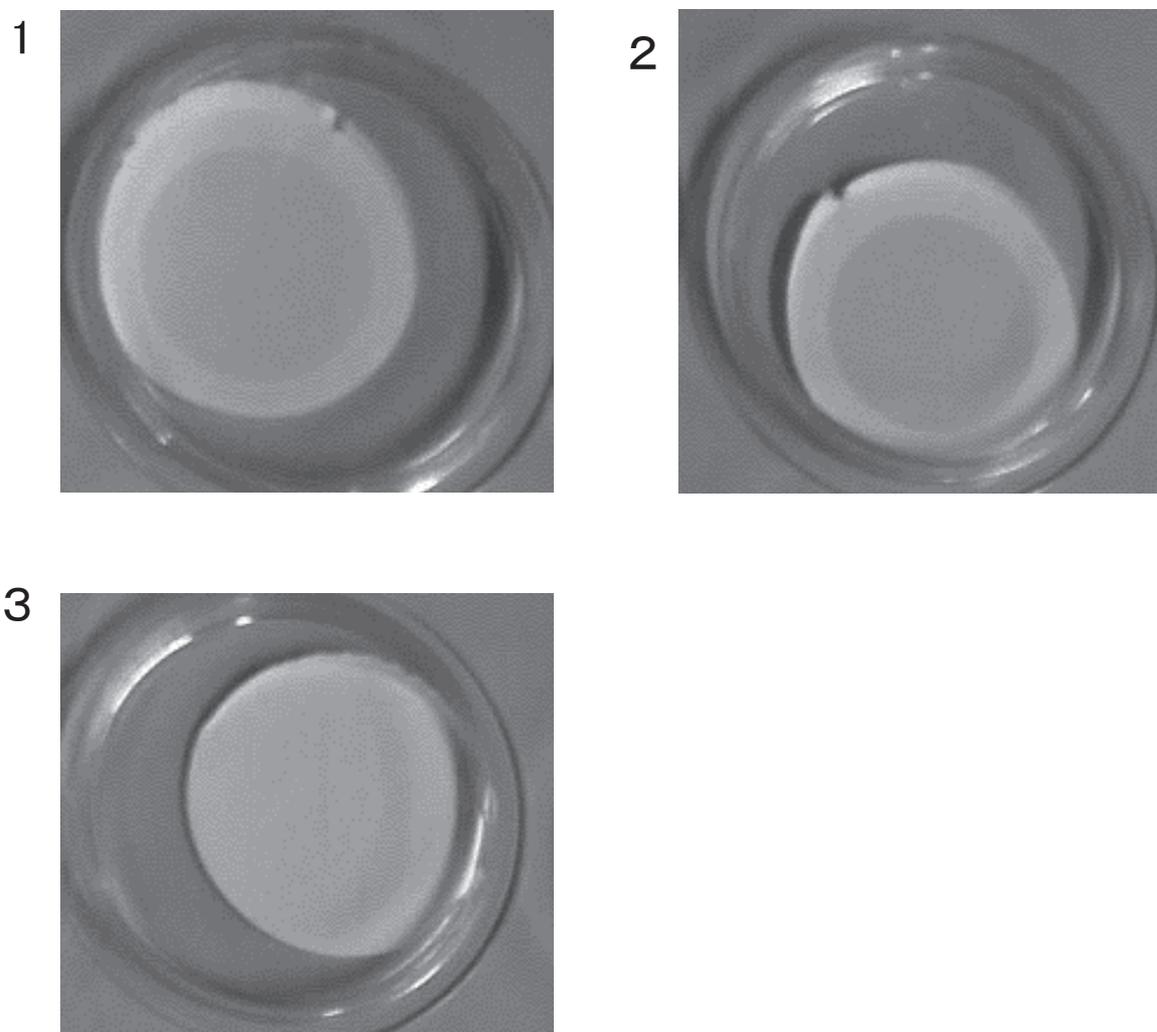


Fig. 4. Photographs of filters colored due to particle collecting. 1: sampling in Fa-A, 2: sampling in Fa-B, 3: sampling in FB-a, respectively.

Table 2.  $\text{TiO}_2$  concentrations in the workplace air as titanium measured by X-ray fluorescence spectrometry and estimated  $\text{TiO}_2$  concentrations from optical particle counting by means of OPS

Sample ID	(A) $\text{TiO}_2$ conc. on filters <sup>†</sup>	(B) Sampled volume/L	(C) $\text{TiO}_2$ conc. in workplace air <sup>†, ‡</sup>	(D) Estimated $\text{TiO}_2$ concentration from OPS counts <sup>†</sup>
FA-a	$24.0 \pm 0.07^*$	2,147	0.055	N/A <sup>‡‡</sup>
FA-b	$9.0 \pm 0.04^*$	1,479	0.030	N/A <sup>‡‡</sup>
FB	$4.2 \pm 0.03^*$	2,086	0.098	0.23

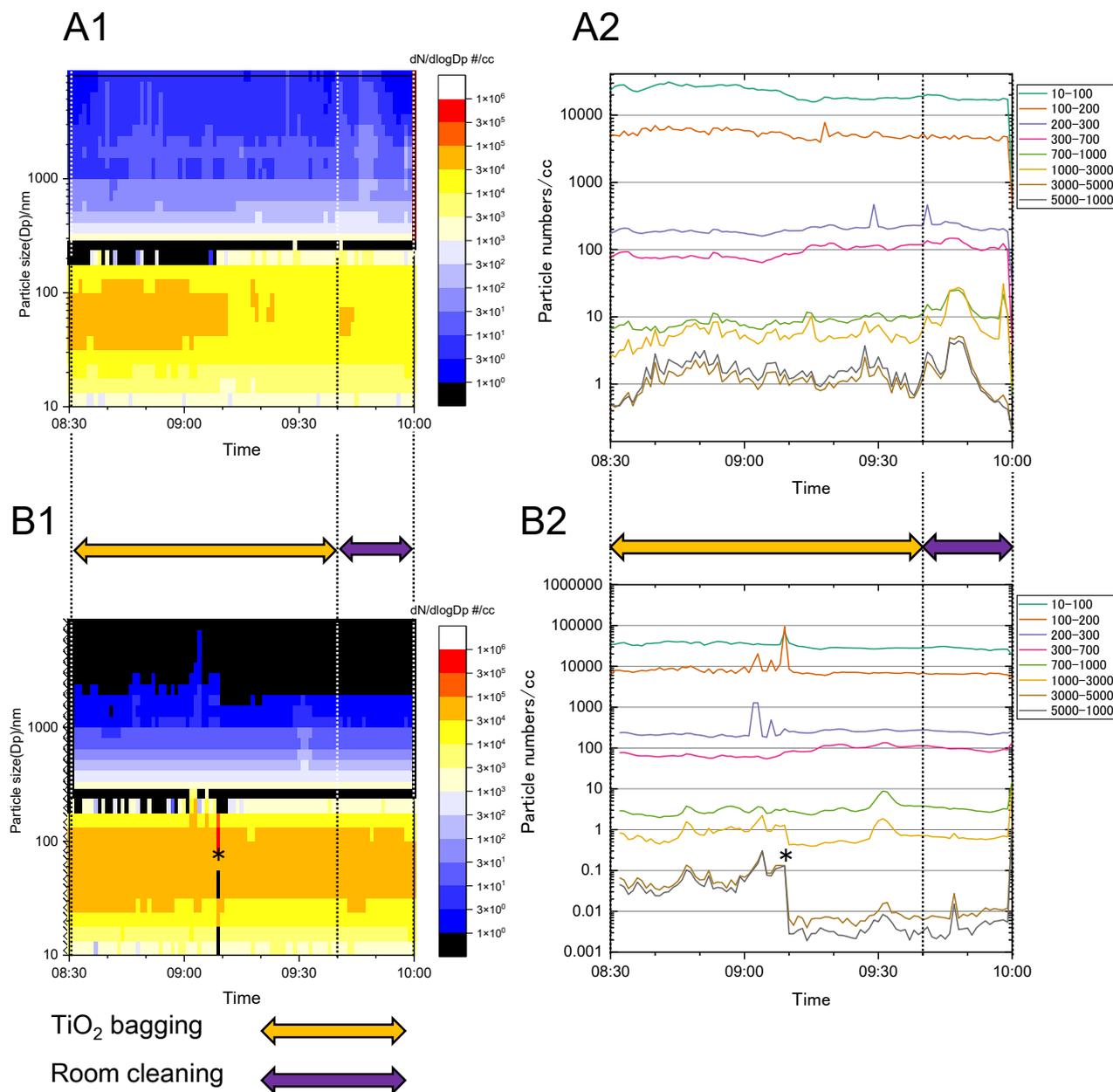
<sup>†</sup> The concentrations units are (A):  $\mu\text{g}/\text{cm}^2$  as Ti, (C) and (D):  $/\text{mg}/\text{m}^3$  as Ti, respectively.

\* Statistical errors of X-ray counts.

<sup>‡</sup> (C)  $[\text{mg}/\text{m}^3] = (\text{A}) [\mu\text{g}/\text{cm}^2]/1,000 [\mu\text{g}/\text{mg}] \times 4.19 [\text{cm}^2]/((\text{B})/1,000 [\text{L}/\text{m}^3])$ .

Here:  $4.19 \text{ cm}^2$  is the effective filtering face of NW354.

<sup>‡‡</sup> N/A: Not available. The particle number concentrations of FA-a and FA-b were not clearly differentiated from the background concentrations.



**Fig. 5.** Contour maps (A1, B1) and particle number concentrations with classified size ranges (A2, B2) showing the time course of particle size distribution in FA-a. **A:** sampled near bagging task. **B:** sampled far from bagging task location at 9:10 (shown as \*) in B2 and adjacent section from the bagging section the plant in the same building for background data. The moving sampling location was due to avoiding interfere to another worker who was carried out non-bagging task.

those in B1 and B2 due to the effect of the push–pull ventilation system. However, it was difficult to confirm the generation of particles during work, which did not significantly differ from the background level. The measurement point B was moved to another section because of operations other than bagging, in the same room at a certain distance from the workplace (marked (\*) in B1 and B2 in Fig. 5). A change in the concentration of large particles was observed as the distance from the workplace increased. However, the

concentration of nanoparticles did not change. One peak could be observed in the SMPS result near (\*). Some noise peaks associated with air turbulence were also observed when moving the devices, indicating that the particle concentration did not change.

Fig. 6 presents the data acquired in FA-b without the push–pull ventilation system.

Moreover, operations related to submicron- and nano-sized particle releases were performed in FB (Fig. 7). There

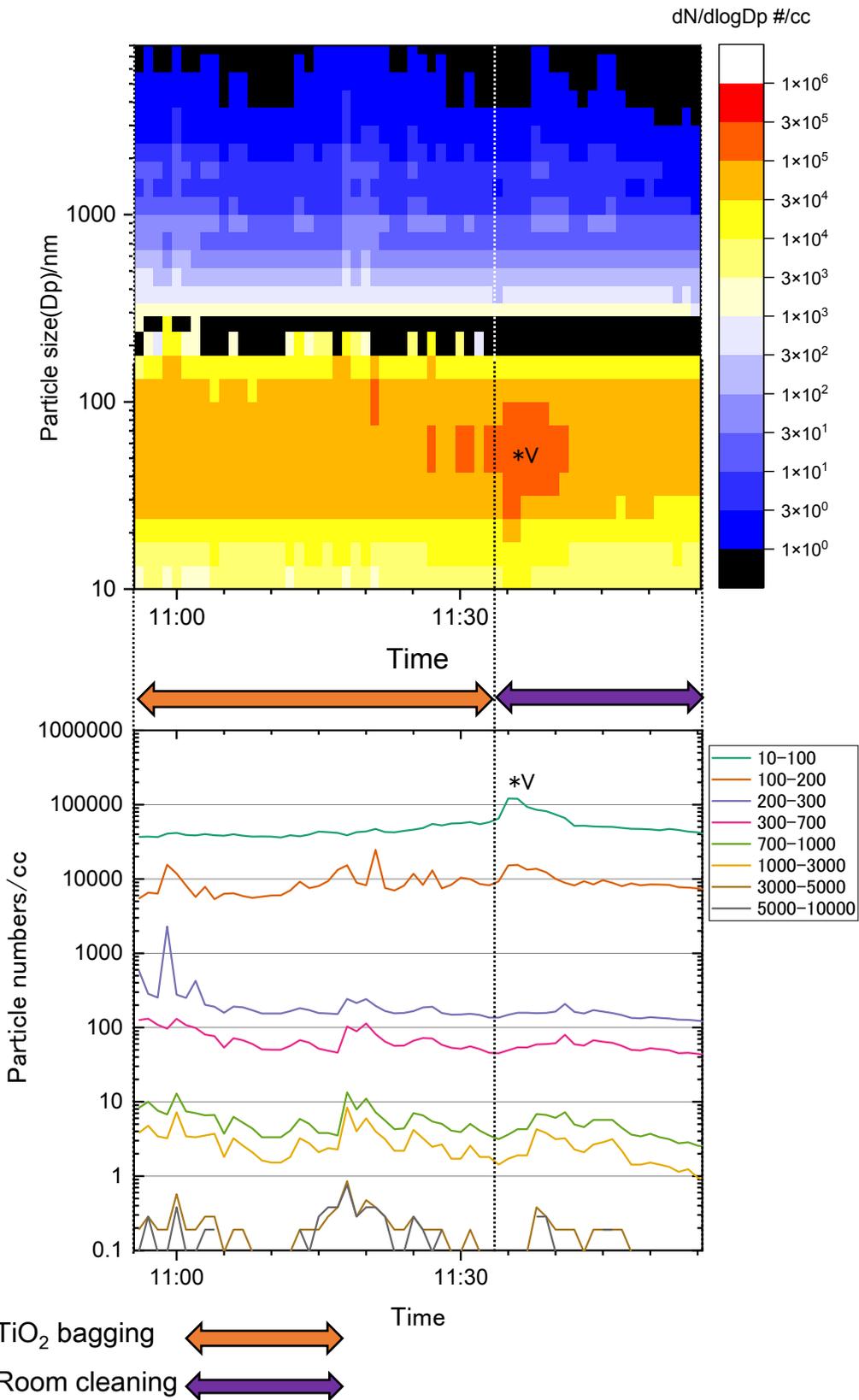
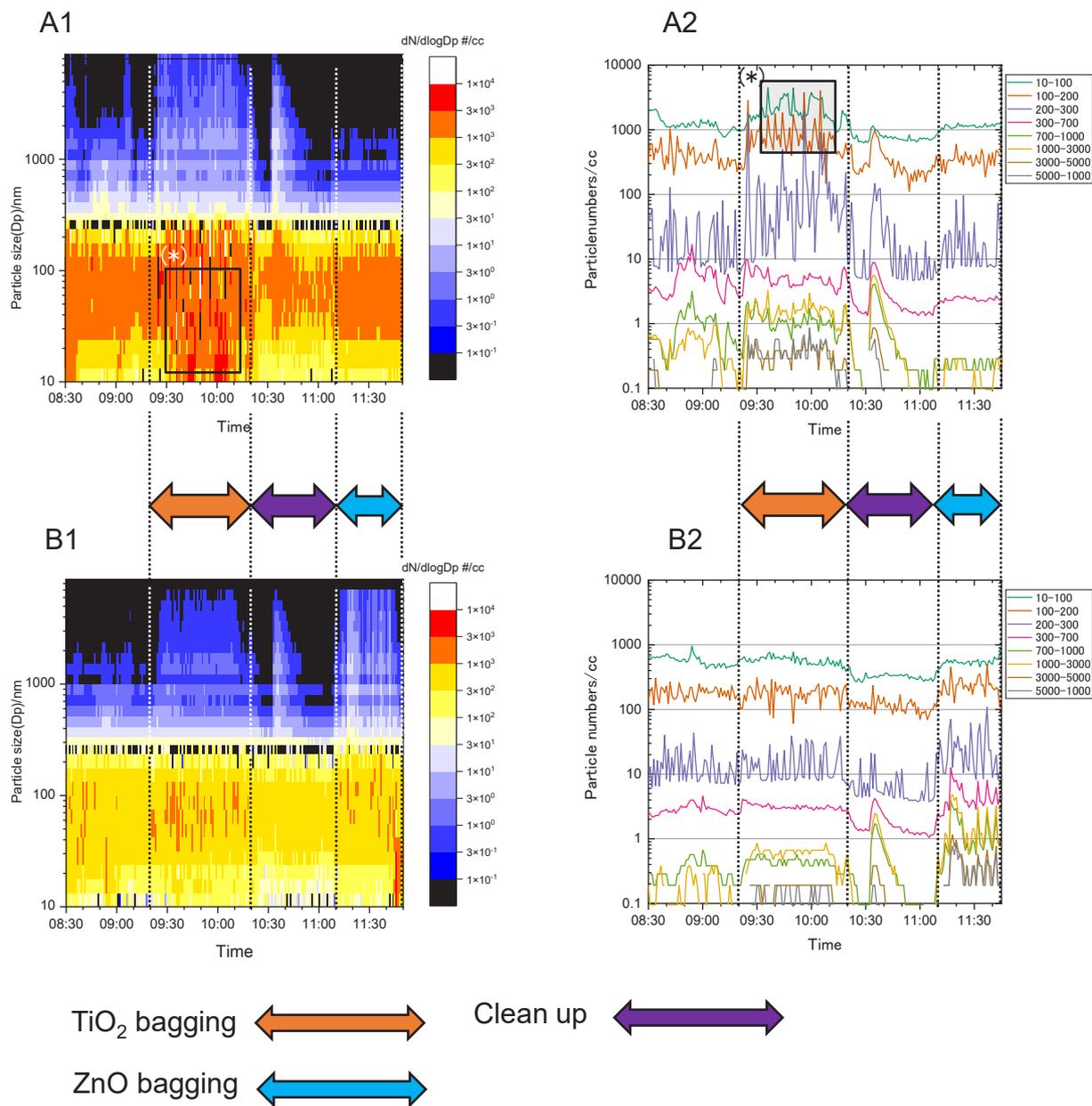


Fig. 6. Contour map and particle number concentrations with classified size ranges showing the time course of particle size distribution in FA-b. \*V: Vacuum cleaner operated.



**Fig. 7.** Contour maps (A1, B1) and particle number concentrations with classified size ranges (A2, B2) showing the time course of particle size distribution in FB-a and FB-b. A: sampled near hopper a (FB-a) from which nanotitanium dioxide put into the plastic bags. B: sampled near hopper b (FB-b) from which nanozinc oxide put into the plastic bags. (\*): Individual nanoparticle release observed.

were two hoppers in FB, and two bagging operations were conducted in sequence. The first operation was the nano-TiO<sub>2</sub> bagging process in FB-a, and the second operation was the nano-ZnO bagging process in FB-b. During the first operation, the release of nanoparticles was observed at FB-a, where bagging occurred, as well as FB-b, approximately 3 m away from the bagging location. However, the

difference was not statistically significant. During the second operation, a similar trend was observed in the airborne particle concentration; however, the number concentration in the case of the nano-ZnO bagging process was lower than that in the case of the nanoTiO<sub>2</sub> bagging process. Based on the size-selective particle number concentration, the calculated contribution of nanoTiO<sub>2</sub> (<100 nm) in terms

of exposure near the two hoppers was 0.03%.

## Discussion

As presented in Table 2, the order of magnitude of the measured and XRF results of the  $\text{TiO}_2$  concentration estimated using the OPS count values was the same. However, due to a lack of data, such as particle shape and bulk density, the values for OPS calculation differed. In the cases of the XRF analysis of filtered samples, the sample thickness can induce analytical errors. We measured the same PVC-filtered samples using a different XRF instrument with lower X-ray power in a previous study<sup>27</sup>. The intensity of the XRF signals of the substrate on which the PVC filter was placed was sufficient<sup>27</sup>. As a result, we believe that the thickness of the apparatus used in this study was sufficient for X-ray observation of PVC-filtered samples. The estimated lower limit of quantitation (LOQ) of the measurement obtained from the calibration curve was approximately  $0.12 \mu\text{g}/\text{cm}^2$ . The Ti concentrations in the filtered sample ranged between 4.2 and  $24 \mu\text{g}/\text{cm}^2$ , which were sufficiently larger than the LOQ values. The LOQ value was approximately  $0.0029 \text{ mg}/\text{m}^3$  based on stationary sampling with a low-volume air sampler, assuming an air volume of 200 l sampled at a flow rate of 20 l/min for 10 min, with an effective collection area of approximately  $4.91 \text{ cm}^2$  (using the 35-mm-diameter filter). Furthermore, the calculated LOQ value of personal exposure to Ti in airborne particles was approximately  $0.0008 \text{ mg}/\text{m}^3$  in a typical personal airborne particle sampler, assuming an air volume of 480 l sampled at a flow rate of 2.0 l/min for 4 h, with an effective collection area of approximately  $3.14 \text{ cm}^2$  (using the 25-mm-diameter filter). The estimated LOQ values were lower than  $0.03 \text{ mg}/\text{m}^3$ , which is the 1/10 concentration of the recommended OEL value of  $0.3 \text{ mg}/\text{m}^3$ . Therefore, the XRF analysis was useful in both stationary measurement and personal exposure measurement applications.

The results indicate that XRF analysis is well suited for the evaluation of occupational  $\text{TiO}_2$  exposure risks during powder bagging processes. However, the XRF analysis presented in this study has the following limitations. In the case of a solid-sample analysis without dissolution, the accuracy of the analysis is determined by the sample thickness and the size and shape of the sample particles. In this instance, the calibration curve was obtained by preparing a standard sample set by adding suspension liquid to the media, and the results may show some deviations. However, we believe that the analytical procedure using XRF is a useful method for the evaluation of  $\text{TiO}_2$  exposure risk be-

cause the wet analysis of chemical-resistant  $\text{TiO}_2$  and the gravimetric determination of high concentrations of workplace background particles are extremely difficult with a high frequency.

The FA result suggests that the particle number measurement is not a viable option for evaluating nanomaterial exposure in a factory where nonfiltered outdoor air is introduced due to high concentrations of environmental particles. This result is consistent with the findings of many previous studies. The concentrations of both nanosized and submicron-sized particles fluctuate with the changes in the concentrations of background particles. The concentration of micron-sized particles closely corresponds to operations performed by workers and serves as a good index for relative exposure. However, the result of particle number concentration cannot be directly converted into the evaluation of mass concentration. In the result presented in Table 2, the estimated result of the particle number concentration considerably differs from the analyzed XRF result because the assumed values of the particle shape and density did not match those of the real  $\text{TiO}_2$  particles in the workplace. Because of loose agglomeration, the bulk-specific gravity of larger, micron-sized particles is expected to considerably differ from the density of  $\text{TiO}_2$ , even though micron-sized particles make a greater contribution than nanoparticles to mass concentrations in the workplace environment. Due to current knowledge limitations, the particle number concentration measurement for quantitative exposure evaluations necessitates simultaneous microscopic observations and/or chemical analyses. The particle number concentration measurement has limited applicability to relative risk estimations, i.e., task improvements and ventilation effect evaluation.

Fig. 7 presents considerable qualitative information on the behavior of nanoparticles in the workplace. The elimination of background particles indicates the existence of nonagglomerated nanoparticles in the vicinity of employees, not only near the working hopper but also 3 m away from the bagging position; nevertheless, it does not provide quantitative information. As can be seen from the upper graph of Fig. 7, the NanoScan result is sometimes 0 during the nano $\text{TiO}_2$  bagging process, possibly due to the rapid concentration fluctuation during scanning, the overflow of larger particle elimination cyclones, and DMA errors attributed to the electrostatic charging of particles because of powder falling from the hopper. Consequently, it is difficult to quantitatively assess the exposure risk of nanoparticles using NanoScan, even in the absence of background particles during the powder bagging process.

When estimating the contribution of nanoparticles to total TiO<sub>2</sub> exposure, the calculated result was 0.03% in front of the hopper. Fig. 7 qualitatively demonstrates that the nonagglomerated nanoparticles diffused the other sampling location, which was ~3 m away from the hopper. Further, nanoparticle exposure occurred during the nano-ZnO bagging process; however, the concentration of these nanoparticles was the same as that in locations that did not involve bagging processes. This study has two main limitations. We did not obtain real background data owing to factory management limitations. Even without bagging operation, the concentrations were not strictly at the background level. Because some workers entered the room for other operations during the measurement, the particle concentration could increase compared with the real background level. Moreover, the sampled particles were not subjected to electron microscopic observations. Because of these limitations, the increase in the nanoparticle concentration was not completely attributed to the release of nanomaterials.

Herein, the main concern to address is whether workers are exposed to nanoparticles when handling powder. Our answer is “yes in the case of TiO<sub>2</sub>”. This answer is based not only on the results presented in this study but also on other data. The NIOSH conducted a powder-handling simulation experiment in a chamber where HEPA-filtered air was introduced. At a distance of 1.3 m from where the powder was placed in a paper bag with a scoop, the nanoparticles in the mass ratio were 1% and 0.5% for bare TiO<sub>2</sub> and hydrophobic-treated TiO<sub>2</sub> powders, respectively<sup>28</sup>. Fronseca *et al.* reported similar results in simulated task studies<sup>29</sup>. The results obtained from the simulated experiment and those obtained from the actual workplace differed in the current study. We believe that these differences are attributed to fluctuations in operation details and nanomaterial handling.

Since nanomaterials have become a new concern in the field of occupational health, a question has arisen whether the health effects of the nanoparticles associated with these nanomaterials are comparable to those associated with larger aggregated particles. The question has not yet been fully addressed, as it is difficult to construct an experimental system that quantitatively measures the nanoparticle diffusion of nanomaterials. If workers are not regularly exposed to nanoparticles, the question would only have an academic value. However, the results of the present study indicate that workers are constantly exposed to nanoparticles emanating from nanomaterials. Therefore, this issue is crucial in occupational health and has now been addressed, at least in the case of TiO<sub>2</sub>.

## Conclusions

In this study, we observed the behaviors of nanoTiO<sub>2</sub> particles in two nanomaterial-handling factories and employed nanoparticle-measuring methods to measure the particle number concentration. The following results were obtained: 1) nonagglomerated particles with sizes of <100 nm or small aggregated particles of TiO<sub>2</sub> will be released while handling nanoTiO<sub>2</sub> powders; 2) in the presence of both nanosized and submicron-sized particles, the separable particle concentration measurements of the workplace air would be somewhat unsuitable for the particles present in the background air; and 3) XRF analysis is an effective method for evaluating TiO<sub>2</sub> exposure.

## Conflict of Interest

The authors have no conflicts of interest to declare.

## Acknowledgments

This study was based on a survey conducted and evaluated by members of the Committee for “Research and development of analytical methods for the exposure assessment of nanomaterials”. This committee was established by the Japan Industrial Safety and Health Association (JISHA), entrusted by the Japan Ministry of Health, Labour and Welfare (MHLW), and chaired by Professor Emeritus Dr. Toshio Nagoya (Waseda University). Finally, we would like to convey our appreciation to the many colleagues of Higashikubo at JISHA and their efforts in contributing to the present survey.

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