EVALUATION OF OCCUPATIONAL EXPOSURE TO TiO_2 NANOPARTICLES: MICROWAVE-ASSISTED ACID DIGESTION METHOD ON AIR MEMBRANE FILTERS

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Abstract

Titanium dioxide (TiO_2) nanoparticles have been extensively used in various industrial sectors and applications, including cosmetics, catalysts, food additives, inks, paints, and coatings. However, the International Agency for Research on Cancer (IARC) has classified TiO_2 nanoparticles as a potential carcinogen for humans, meaning they may cause cancer and pose serious health complications, particularly for manufacturing workers. This highlights the need for better evaluation to determine worker exposure. In this study, suspended TiO_2 nanoparticles were sampled using a nanoparticle respiratory deposition (NRD) sampler fitted with specially designed membrane filters and analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The digestion method used for titanium element recovery after nanoparticle sampling is crucial for optimal ICP-MS analysis. Therefore, this study aimed to investigate the most suitable digestion method. A microwave-acid digestion method using concentrated nitric acid and concentrated hydrochloric acid at a 7:4 ratio, with a run time of 30 minutes and the temperature set to 200°C showed remarkable titanium recovery compared to other methods. These findings may pave the way for optimal analysis of suspended TiO_2 nanoparticles in assessing occupational exposure while promoting sustainability and eco-friendliness in resource utilization.

Keywords: Nanoparticles, Occupational Health, ICP-MS, Workplace, Titanium Dioxide

Introduction

Nanoparticles are incredibly tiny particles that measure between 1 to 100 nanometres (1). It has unique physicochemical properties such as high surface area, reactivity, and size-dependent optical and electronic properties, which make them highly desirable for numerous industrial applications including drug delivery, electronic devices, energy storage, catalysis, and environmental remediation (2-4). Some of the nanoparticles commonly known in manufacturing industries include titanium dioxide (TiO_2), aluminium oxide, carbon nanotubes, silica, and copper (5-7).

Despite the benefit of nanoparticle application, it was discovered that the nanoparticles could pose health risks by penetrating deep into the lungs, causing inflammation, oxidative stress, genotoxicity, and respiratory and cardiovascular disorders (8). Exposure to suspended nanoparticles over an extended period, particularly through inhalation, at high levels can have harmful effects on the health of individuals working in occupational environments. Song et al. (9) found that seven female workers with exposure to nanoparticles for 5-13 months experienced pulmonary inflammation, fibrosis, and foreign-body granulomas of the pleura through pathological examinations. Another finding reported that a few workers were diagnosed with an assumed respiratory work-related illness after handling and manufacturing nanomaterials in their workplace environment (10).

TiO_2 is is commonly used as a white pigment because of its high refractive index and ability to scatter light and it has two types of crystal structures, namely anatase and rutile (11). The TiO_2 fine particles and TiO_2 nanoparticles have a significant difference in their physicochemical properties, while the latter has also been widely used in the industrial sectors due to higher stability, anti-corrosive and photocatalytic properties. International Agency for Research on Cancer (IARC) has classified the TiO_2 nanoparticles as IARC Group 2B carcinogen, which is "possibly carcinogenic to the human" based on evidence obtained from animal studies (12). Despite some studies reporting inadequate evidence of epidemiological studies for the human to develop cancer from exposure to TiO_2 nanoparticles through inhalation (11), nonetheless, the workers that were exposed to high concentration, prolonged exposure of the TiO_2 nanoparticles still possessed a great risk to develop health complications.

The potential health effects posed by nanoparticles have raised concerns. As a result, there is a need for suitable methods of exposure evaluation in occupational environments, including sampling and analysis. The objective of this study is to determine a suitable digestion method for the specially designed membrane filters that could effectively capture suspended TiO_2 and optimize its analysis using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Accurately determining worker exposure to nanoparticles using ICP-MS analysis depends significantly on choosing the appropriate membrane filter digestion method. Therefore, it is critical to select a suitable digestion method that can effectively break down the membrane filter material while minimizing interference and background levels.

Materials and Methods

Suspended titanium dioxide nanoparticles sampling

A mixture of 0.3 mg of TiO_2 nanoparticle powder, containing 0.1 mg of TiO_2 nanoparticles of different sizes (30 nm, 50 nm, and 100 nm), was prepared in the Buchner flask. The flask was placed in the oven for 15 minutes at 40^{o}C to remove any air moisture. Then, the flask containing the TiO_2 nanoparticles mixture was connected to the vacuum pump and air regulator with pre-determined airflow to mimic the inhalation and exposure of nanoparticles suspended in the air. The setup was also connected with a nanoparticle respiratory deposition (NRD) sampler equipped with different types of specially designed membrane filters namely NS01, NZ01 and NG01. Figure 1 displayed the set-up of the suspended TiO_2 nanoparticles sampling. The flow rate controller was adjusted to 2.5 litres per minute, which followed the range of flow rate of NIOSH Manual of Analytical Methods 7302 (NMAM), and the exposure testing was conducted for 15 minutes for each sampling using the NRD sampler equipped with NS01, NZ01 and NG01 filters, separately. The procedure was performed in triplicate for each filter, which then was taken for further ICP-MS analysis to investigate the sampling efficiency.

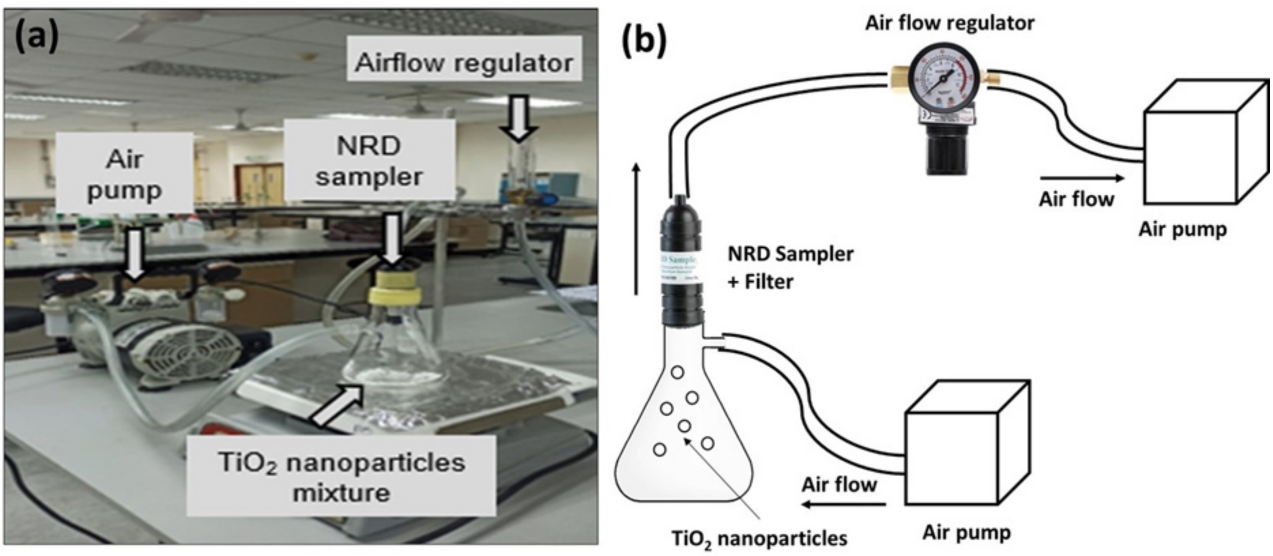

Figure 1: Digital image (a) and schematic illustration (b) of suspended TiO_2 nanoparticles sampling set-up.

Preparation of standard solution

Five mL of stock solution (1000 ppm) was added into 50 mL of a volumetric flask to produce an intermediate solution with a concentration of 100 ppm. Five 50 mL volumetric flasks were filled with 0.00 mL, 0.25 mL, 0.50 mL, 1.00 mL, and 2.5 mL of intermediate solution (100 ppm) respectively using the pipette. Another 50 mL volumetric was pipetted with 2.5 mL of a stock solution that act as a control in the sample preparation. Each of the volumetric flasks was filled with 2% nitric acid to produce 0.0 ppm, 0.5 ppm, 1.0 ppm, 2.0 ppm, 5.0 ppm and 50.0 ppm, respectively.

Microwave acid digestion

The ICP-MS analysis was performed by digesting the membrane filter samples using microwave-assisted acid digestion technique for sample preparation. Two different acid decompositions were used in this study, namely Mixture A and Mixture B. The amount of titanium representing the TiO_2 nanoparticles recovered from each membrane filter was compared to investigate the efficiency between NS01, NZ01, and NG01.

Microwave acid digestion – Method A

The dried sample was transferred into the digestion vessel before being introduced into the hydrothermal carbonization (HTC) safety shield. The acid digestion mixture, consisting of 7 mL of 65% nitric acid (HNO_3) and 4 mL of 37% hydrochloric acid (HCl), was added to the digestion vessel to dissolve the sample. Subsequently, the vessel was tightened using the machine. The vessel then was placed in the microwave that was set at 200 ºC for 30 minutes to ensure the sample was completely dissolved for trace metal analysis. The sample solution was transferred into a 50 mL volumetric flask before being diluted to the mark with 2% nitric acid. Each of the digested samples was closed and labelled properly before being analysed with the ICP-MS.

Microwave acid digestion – Method B

The dried sample was transferred into the tetrafluoromethoxyl (TFM) vessel before being placed inside the HTC safety shield. An acid digestion mixture that consisted of 6 mL of 99% HNO_3 and 3 mL of 96% H_2SO_4 was added to the digestion vessel before being tightened. The vessel was then placed in the microwave at a temperature of 210^{o}C for 45 minutes to dissolve the sample for trace analysis. The sample solution was transferred into a 50 mL volumetric flask before being diluted with 2% HNO_3 to the mark. The digested sample was closed and labelled properly before being analysed with the ICP-MS. Table 1 shows the summary of microwave acid digestion method conditions for mixtures A and B.

Table 1: Overall specification on both methods used for sample preparation

Method	A	B
Acid Digestion Mixture	Nitric acid (65% HNO_3) + hydrochloric acid (HCl) (7:4)	Nitric acid (99% HNO_3) + sulphuric acid (H_2SO_4) (1:2)
Digestion Temperature (ºC)	200	210
Digestion Time (minute)	30	45

Ethical considerations

Ethical clearance for this study was obtained from the International Islamic University Malaysia (IIUM) Research Ethics Committee (IREC) with reference code IREC 2019-248. The study protocol and experimental procedures were reviewed and approved by the committee, ensuring compliance with ethical standards in research conduct. The experiment was conducted following the approved protocol, emphasizing research integrity, safety, responsible resource utilization, data management, and open science principles.

Results

The average concentration of Ti

The results of ICP-MS analysis for an average concentration of Ti recovered from triplicate samples of each type of membrane filter prepared using two different sample preparation methods are summarised in Table 2. The study found that the highest average concentration of Ti was obtained using digestion method A for membrane filter NZ01, followed by NS01, and NG01 (159.97 ± 9.49 mg/m^3, 110.98 ± 4.12 mg/m^3, and 11.70 ± 0.55 mg/m^3, respectively). Similar results were observed by using digestion method B, the highest average concentration of Ti is NZ01, followed by NS01 and NG01 (17.95 ± 3.11 mg/m^3, 8.98 ± 1.16 mg/m^3, and 4.57 ± 0.66 mg/m^3, respectively).

Table 2: ICP-MS results for each membrane filter using different digestion methods

Type of Filter	Method A	Method B
	Average concentration (mg/m^3)	**Average concentration (mg/m^3)**
NS01	110.98 ± 4.12	8.98 ± 1.16
NZ01	159.97 ± 9.49	17.95 ± 3.11
NG01	11.70 ± 0.55	4.57 ± 0.66

Ti recovery between the digestion method

Figure 2 shows the recovery of Ti using both digestion methods and different types of membrane filters. Digestion of membrane filter NS01 shows that method A obtained more Ti recovery than method B (110.98 mg/m^3 and 8.98 mg/m^3 respectively). Similar observations were also reported for NZ01 (159.97 mg/m^3 and 17.95 mg/m^3, respectively) and NG01 (11.70 mg/m^3 and 4.57, respectively).

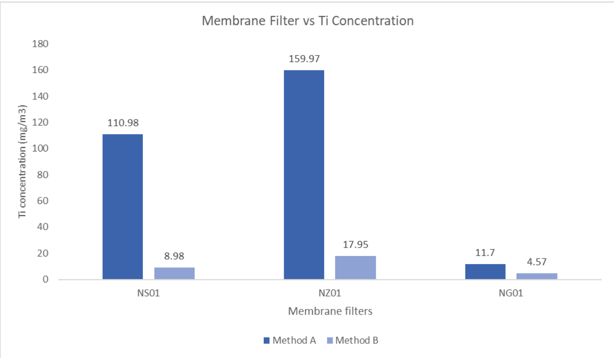

Figure 2: Recovery of titanium using two different acid digestion methods and different types of membrane filters.

Discussion

Sampling and sample preparation are both critically important for measurement for quantitative analysis of any trace element analysis. In this work, the sampling of TiO_2 nanoparticles was investigated using two digestion methods with different combinations of concentrated acids that were introduced to ensure that collected samples have been fully digested before the analysis. Many important factors need to be considered in choosing the suitable sample preparation technique such as the open or closed digestion system, the composition of the digestion acid mixture, and digestion time at a specific temperature. The TiO_2 was considered one of the least soluble metal oxides that required a strong oxidizing agent to break down the lattice structure completely for the quantitative analysis (13). Incomplete digestion of the samples due to poor recoveries could affect the determination of the total concentration of Ti.

In this study, two different methods were used to analyse the exposed membrane filters (NS01, NZ01, and NG01) to determine which filters and digestion method would yield higher recovery of titanium during quantitative analysis. Method A is considered an improved method, as described in the UltraWAVE Application Book published by Milestone (14). This method uses a mixture of HNO_3 and HCl (in a ratio of 7:4) as the digestion acid mixture (referred to as "mixture A"). On the other hand, Method B was adapted from the work of Mundukotuwa et al. (13) and uses a digestion acid mixture consisting of concentrated H_2SO_4 and HNO_3 (in a ratio of 2:1) (referred to as "mixture B"). Table 2 summarized the results of ICP-MS analysis for an average concentration of Ti recovered from triplicate samples of each type of membrane filter prepared using two different sample preparation methods.

Based on the analysis, there is a significant difference in the concentration of Ti obtained when using a different type of digestion acid mixtures for the sampling of the Ti nanoparticles as shown in Figure 2. Method B, which was adopted from Mudunkotuwa et al. (13) work, only retrieved a small quantity of titanium that was previously trapped on the membrane filters. Furthermore, method B only achieved a total recovery of approximately 10% of the titanium compared to using method A digestion mixture, which recovered a higher percentage of the total titanium. This suggests that method B may not be as effective in recovering titanium as the other methods tested in the study. The study found that method A was the most effective approach for analysing suspended TiO_2 nanoparticles, utilizing specially designed membrane filters (NS01, NZ01, and NG01). Furthermore, the study found notable differences in TiO_2 nanoparticle sampling effectiveness depending on the type of membrane filter used. The NZ01 membrane filter displayed better performance compared to the NS01 and NG01 membrane filters. In contrast, the results obtained from the NG01 membrane filter were notably lower than those achieved with the other two membrane filters. This discrepancy may be attributed to incomplete dissolution resulting from the material characteristics of the NG01 membrane filter. In addition, the study identified that the use of HNO_3 and HCl was effective in improving the yield of titanium recovery. The composition of HNO_3 and HCl with a mixture ratio of 2:1 v/v was known as reverse aqua regia usually used for metal samples in the sample preparation (15). Both aqua regia and reverse aqua regia were the common digestion method used for sediment and sludge samples to determine the trace of the heavy metals. HNO_3 was usually used as a digestion acid due to its strong oxidative properties, and with the addition of HCl, the digestion of organic matter, sulphides, carbonates, and phosphates could be achieved (16). The reaction between TiO_2 with hot, concentrated hydrochloric acid and nitric acid would form titanium nitrate ($Ti(NO_3)_4$) and titanium tetrachloride ($TiCl_4$), respectively. The general equations for the chemical reaction are as follows:

$$4\ HNO_3\ (aq) + TiO_2\ (s) = Ti(NO_3)_4 + 2\ H_2O\ (l) \quad (1)$$

$$4\ HCl\ (aq) + TiO_2\ (s) = TiCl_4\ (aq) + 2\ H_2O\ (l) \quad (2)$$

Overall, method A demonstrated a higher recovery of titanium during microwave acid digestion compared to method B. Moreover, method A had a shorter digestion time of only 30 minutes, whereas method B required 45 minutes for the digestion process. The shorter digestion time of method A (30 minutes) compared to method B (45 minutes) could provide a significant benefit in terms of time efficiency. More samples can be processed in less time, increasing the pace and productivity of the research. This is especially useful when analysing large numbers of samples or when time is of the essence in the investigation.

Conclusion

In conclusion, the in-situ sampling of suspended TiO_2 nanoparticles was successfully achieved using various specially designed membrane filters. The ICP-MS analysis revealed a significant difference in Ti recovery when using different acid digestion techniques and the amount of TiO_2 nanoparticles captured was also dependent on the type of filter used within the NRD sampler. Method A, which used the combination of concentrated HNO_3 and concentrated HCl managed to obtain remarkably higher Ti recoveries as compared to method B, which obtained only 10% of Ti recovery. In addition, the membrane filter NZ01 provides the most efficient trapping of suspended TiO_2 nanoparticles with a Ti recovery concentration of 159.97 ± 9.49 mg/m^3 followed by NS01 (110.98 ± 4.12 mg/m^3) and NG01 (11.70 ± 0.55 mg/m^3). This work might pave the way towards optimum TiO_2 sampling analysis via ICP-MS and will unlock various research opportunities in the evaluation of nanoparticle exposure towards workers.

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Competing interests

The authors declare that they have no competing interests.

Ethical clearance

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