



## A REVIEW: THE PHYSICOCHEMICAL CHARACTERISTICS OF INDOOR PARTICULATE MATTERS IN RELATION TO HUMAN HEALTH

Indri Santiasih<sup>1</sup> and Joni Hermana<sup>2</sup>

<sup>1</sup>Safety Engineering Department, Shipbuilding Institute of Polytechnic Surabaya, Indonesia

<sup>2</sup>Environmental Engineering Department, Institute Teknologi Sepuluh Nopember, Indonesia

E-Mail: [indri.santiasih@ppns.ac.id](mailto:indri.santiasih@ppns.ac.id)

### ABSTRACT

Particulate matters exposure significantly affects human health, especially for those who are working indoor such as in a workplace, house, office, laboratory and vehicle. The objective of this paper is to review the existing physicochemical characteristics of particulate matters from their various sources, to investigate the differences and similarities and the effect of emission sources. Which largely influences the size, the shape, and chemical compound? The result shows that the physicochemical characteristics may exacerbate human health.

**Keywords:** particulate matters, indoor, physicochemical characteristics, human health.

### INTRODUCTION

In the last two decades, indoor air quality is interesting scientific in relation to particulate matter (PM) pollution[1]. PM is a solid and water suspension in ambient air. It is well known that PM is common in ambient air, indoor and outdoor environment. In different way, PM indoors may originate from outdoor discharged to indoor or be naturally generated in indoor[2]. However, different indoor environments depends on different indoor or outdoor sources and they related each other. Almost all of anthropogenic activities [3-5]emit PM in different characteristics. Generally, human activities were majority occurred in indoor (80%) [6]. Accordingly, indoor exposure is very important to be considered; due to a low level exposure in a long duration produced a significant accumulation effect. The exposures could be derived from any indoor activities and properties such as inside workplace (industrial process), inside a house (cooking, cleaning, material building, surface coating), inside a vehicle (combustion, air freshner), and inside an office (copying machine, printer).

Particulate matters also have been interesting scientists since it had been influenced human exposure as common gas of indoor pollutants. Some scientist investigated health impact of PM in respiratory, cardiovascular, cellular effect [7-12]. Two parameters of PM which dangerous to human are chemical and physical properties [13]. The chemical and physical property of PM is influenced by PM source, which determine atmospheric behaviour of PM. Actually, indoor PM characteristics was not really different from outdoor. Its characteristics included physical (size, shape of) and chemical characteristics (chemical constituent), which provided PM toxicity to human who was exposed.

Several researches discussed about PM toxicity in relation to physicochemical characteristics of PM. Lin *et al.* [14]examined the interrelationship between particulate matter (PM) size and in vitro toxicological effects of mainstream cigarette smoke. They obtained that there were PM of a large size induced less toxicity compared with PM of a small size. The investigation concluded that PM of a small size was more toxic than PM of a large size.

Mar *et al.* [15] examined the association between mortality rate in elderly individuals and particulate matter (PM) of different aerodynamic diameters. Total mortality had a significant association with PM<sub>10</sub>, PM<sub>2.5</sub> and coarse PM. Notter [16] found fiber-shaped particles cause toxicity because of their shape, not their chemical composition. The fiber paradigm identified the geometry of fibers in combination with their biopersistence as their most important toxicological characteristic [17]. Kelly and Fussel [18] investigated PM toxicity related to chemical composition. Lin *et al.* [19] researched the association between particle sizes and their constituents with cardiovascular mortality. The results showed that PM<sub>10</sub>and PM<sub>2.5</sub>, were significantly associated with mortality by cardiovascular cases. It was significantly associated between cardiovascular mortality and sulfate, nitrate, organic carbon (OC), elemental carbon (EC), and ammonium.

The majority people spent most of their time in indoor environment. It is not surprising that people spent greater portion of time (> 80%) in indoor environment [6]. This is a reason why indoor exposure of PM has significant influences to human health, besides its physicochemical characteristics. So it is necessary to understand how PM toxicity according to physical and chemical characteristics, to anticipate both acutely or chronically PM exposed. Because this exposure with a lower level of PM in a long duration provided a significant accumulation, let alone the higher level.

The purpose of this paper is to review the physicochemical characteristics of particulate matters (PM<sub>10</sub>and PM<sub>2.5</sub>) from various emission sources and to investigate the effect of emission sources which influences on their size, shape, and chemical compound.

### INDOOR PARTICULATE MATTER

Particulate matters is an origin complex mixtures of solid particles and aerosol in ambient air. PMs are conventionally defined as suspension between an extremely small of solid or liquid droplets. PM definitions have been briefly defined in several references (Table-1).

**Table-1.** Definition of PM.

Definition of PM	References
A complex mixture of solid and liquid particles which contain primary and secondary origin in composition, and a wide range of inorganic and organic components.	[20]
A complex mixture of organic and inorganic substances. The Mass and composition commonly divided into two groups: coarse particles and fine particles.	[21]
An air gas pollutant consisting of a mixture of solid and liquid particles which has suspended in the air both of indoor or outdoor environment.	[22]
A very small diameter of solids or liquids which suspended in exhaust gases and discharge into the atmosphere.	[23]
A complex mixture of very small solid particles and liquid droplets which found in the air both indoor or outdoor environment.	[24]

Particulate matters (PM) consist solid and/or liquid particles which suspended into the air and generally contain organic and inorganic substances. This substances is largely influenced by the various of emission sources which is affected by production process, type of raw material and material handling[25]. According to the particulate size, they divide into two groups: coarse and fine particles. Coarse particles are particulate matters which consist of particles larger than 2  $\mu\text{m}$  in diameter, whereas fine particles are  $\leq 2 \mu\text{m}$  in diameter[26]. There is two type of PM according to how it was formed, primary and secondary particles. Primary particles are formed by directly emission, whereas secondary particles are formed through chemical reaction between precursor gases and ozone[27].

### Primary PM

Primary of PM is produced by a variation of emission sources, that emit directly as solids or liquids droplets into atmosphere from such as combustions or mechanical activities which generated dusts. The main indoor sources of primary PM are static combustion (principally domestic coal burning) and industrial processes, such as fossil combustion diesel engine or biodiesel engine, construction and cooking stove. The printer machine also produces primary PM beside the secondary one. Generally, primary PM emits black carbon, crustal dust or soil dust, which contains a coarse mode, was showed at Table-2.

### Secondary PM

Secondary particles are consequently formed into the atmosphere as a result of chemical reactions, which producing low volatility substances. It was subsequently condensed into solid or liquid phase, thus flattering a new PM. Additional particulate substances, such as sulfuric acid and its ammonium salts, ammonium nitrate, and a various array of organic compounds, are produced into the atmosphere by reactions between precursors which emitted as gases. This secondary PM could rapidly condense on existing particles, and took shape a new particles through homogeneous nucleation, left behind as a residue of evaporated cloud droplets [28]. The chemical reaction happened if there were precursors emitted gases and ozone in ambient air.

The gases which commonly act as precursor are sulphate, nitrate, sulphur dioxide, nitrogen dioxide and ammonia. Sulphates and nitrates came from the oxidation of sulphur dioxide ( $\text{SO}_2$ ), common power generation and industrial combustion processes. Nitrogen dioxide derived to acids from combustion and tobacco smoke in the atmosphere, and then would be neutralised by atmospheric ammonia, which mainly obtained from agricultural sources such as composting product. Carbonaceous particulates also contain a secondary organic aerosol (SOA) which developed by the oxidation of volatile organic compounds (VOCs). The chemical processes that enlarged formation of secondary particles were relatively slow associated to primary particles and their persistence in the atmosphere was expanded[18].

Ozone  $\text{O}_3(\text{g})$  was produced by photo chemically process in outdoor following photolysis of nitrogen dioxide which is rarely produced indoors because UV sunlight. It is required for its production, so this is usually unavailable indoors. The major indoor source of ozone is outdoor air. Photocopy machines and electrostatic air cleaners emit sufficient UV radiation to produce ozone indoors. In residences and most workplaces, however, ozone mixing ratio, indoors are almost always less than are those in outdoors [26]. Indoor ozone generally existed in order to apply energy efficiency, although this work has not been a smooth progression [29]. Weschler *et al.* [30] investigated that ozone was 60 - 100  $\text{mg}/\text{m}^3$  in ambient air and also inside a carpet. Huang *et al.* [31] researched the chamber with painting wood panel, and they found that formaldehyde concentration significantly increased with ozone addition 200 ppb during 3 hours reaction. Hoang *et al.* [32] investigated ozone removal by green building material. They found that the ceiling from perlite-based was the most reactive to ozone.

Table-2 showed that fossil fuels combustion produce primary small accumulation mode particles, but coagulation and gas-to-particle conversion migrate these particles to the middle and high accumulation modes, Coagulation also migrate them to the coarse mode. Metals evaporate during industrial emissions recondense onto accumulation mode soot particles and coarse mode fly-ash particles, which common the greatest number is iron. Sulfuric acid usually condenses onto accumulation-mode particles in average number because of their a lot surface



area, than nucleation-or coarse-mode particle. Ammonia gas  $\text{NH}_3(\text{g})$  dissolves and dissociates which produce ammonium ion  $\text{NH}_4^+$  are the major-cation in particles to maintain charge balance, therefore ammonium and sulfate often coexist in accumulation-mode particles. Nitric acid

is inhibited to move accumulation-mode particles that already contain sulfuric acid, because sulfuric acid has lower saturation vapor pressure (SVP) and greater solubility than nitric acid [26]. PM emission and indoor sources in different mode is showed in Table-2.

**Table-2.** PM emission and indoor sources.

Emission sources	Primary PM	Primary PM sizes		Precursor gases	Secondary PM sizes		Ref
Construction	Crustal dust, soil dust.	Coarse particle ( $d > 1000 \text{ nm}$ )	Coarse mode	-			[28]
Fossil fuels Combustion (especially diesel engine)	Black carbon	Coarse particle ( $d > 1000 \text{ nm}$ )	Coarse mode	Nitrogen oxide	Ultrafine particles ( $< 100 \text{ nm}$ )	Nucleation, accumulation mode	[26,28,33,34]
	Elemental and organic carbon.	Fine particle ( $d < 1000 \text{ nm}$ )	Accumulation mode	Sulphate	Ultrafine particles ( $< 100 \text{ nm}$ )	Nucleation mode	[35]
Fossil fuels Combustion (especially biodiesel engine)	Elemental and organic carbon	Fine particle ( $d < 1000 \text{ nm}$ )	Accumulation mode	Nitrogen oxide, unregulated emission (sulphate, PAH and nitro-PAH, BTEX, carbonyl).	Ultrafine particles ( $< 100 \text{ nm}$ )	Nucleation, accumulation mode	[26,36]
	Ashes	Ultrafine particles ( $< 100 \text{ nm}$ )	Aitken Mode				[36]
	Crustal metals (Fe, Ca, Mg, Na, Pb, Si, Cu, B, Mn, Cr)						
Material building	-	-	-	Volatile Organic Compound (VOC)	Ultrafine particles ( $< 100 \text{ nm}$ )	Nucleation mode	[37-41]
Printing (jet printing)	-	-	-	Volatile Organic Compound (VOC)	Fine particle ( $d < 1000 \text{ nm}$ )	Accumulation mode	[42,43]
Printing (laser printing)	Carbon black	Coarse particle ( $d > 1000 \text{ nm}$ )	Coarse mode	Volatile Organic Compound (VOC)	Fine particle ( $d < 1000 \text{ nm}$ )	Accumulation mode	[43]
Painting (spray)	Aerosol	Fine particle ( $d < 1000 \text{ nm}$ )	Accumulation mode	Volatile Organic Compound (VOC)	Ultrafine particles ( $< 100 \text{ nm}$ )	Nucleation mode	[44,45]
Cooking (grilling & frying, oven)	-			Sulphur dioxide	Ultrafine particles ( $< 100 \text{ nm}$ )	Nucleation mode	[46]

Volatile organic compound (VOC) evaporates from materials which contain them such as solvents and paints on surface coating appliances, building materials, combustions, varnishes, tobacco smoke, air freshners, cooking, carpets, furniture, and draperies. They can easily evaporate because they have relatively low boiling point (50 to 260°C). Some common VOCs in indoor air include propane, butane, pentane, hexane, *n*-decane, benzene,

toluene, xylene, styrene, acetone, methylethylketone, and limonene, among many others [26].

Formaldehyde  $\text{HCHO}(\text{g})$  was discharged from biomass burning and chemical reaction outdoors, whereas indoor was commonly emitted from indoor surface like insulation appliances as particleboard, furnishings, paneling, and plywood. It was also evaporated from any others indoor properties such as carpets, ceiling tile, furniture and tobacco smoke [26].

**Table-3.** Indoor primary particulate emission dan precursor gases.

Indoor Sources	Primary particle	Aldehyde	Nitrogen dioxide	Sulfur dioxide	Ammonia	Volatile organic compound	Polycyclic aromatic hydrocarbon	References
Painting		X				X		[44,47]
Tobacco smoke	X	X	X			X	X	[26]
Building materials (wall, ceiling, floor)		X				X		[48]
Household properties (carpet)	X	X				X		[47,49]
Cooking stove	X						X	[50]
Air freshener						X		[51]
Cleaning product						X		[52,53]
Fuel combustion (biodiesel engine)	X		X	X			X	[54]
Composting					X			[55]

Nitrogen oxide is chemically produced from oxidation of nitric oxide and it is emitted in small quantities indoors. High short-term mixing ratios of  $\text{NO}_{2(g)}$  occur during the operation of  $\text{NO}_{2(g)}$ -producing appliances. The photolysis of  $\text{NO}_{2(g)}$  and subsequent production of ozone was ignored because UV sunlight does not directly penetrate indoors [26].

Sulfur dioxide is emitted by diesel, coal, gasoline combustion, which does not chemically degrade quickly in gas phase, because hydroxyl radicals  $(\text{OH})_{(g)}$  required to initiate its breakdown, which is not produced indoors.  $(\text{OH})_{(g)}$  came into indoors from the outdoor and then disappears quickly. Losses of  $\text{SO}_{2(g)}$  include deposition to indoor surfaces, dissolution into liquid water (e.g., in bathtubs and sinks) [26]. The summary of indoor primary particulate emission dan precursor gases showed in Table-3.

### PHYSICAL CHARACTERISTIC

The toxic effects of PM depends on both physical and chemical characteristics [36]. Generally, the physical factors that identified as considerable hazards is size and shape of PM.

#### The morphology of PM

The morphologies (structures and shapes) of aerosol particles vary with composition. The older aerosol particles are probable to have the greater number of layers and attachments. If the aerosol particle is hygroscopic, it absorbs liquid water at high relative humidities and becomes spherical. If ions are present and the relative humidity decreases, solid crystals may form within the particle. Some observed aerosol particles are flat, others are globular, others contain layers, and still others are fibrous [26].

Understanding the size and shape of particles is very important to estimate the effect of PM on human health and environment. Particle shape analysis and its effect on human health is a relative new field of investigation because many researchers are focusing on

understanding the relationship between particle's shape and its affect on human health. The morphology of atmospheric particles was a significant subject recent years due to the effect of the particle shapes on their chemical characteristics[24]. Shandilya and Kumar [56] investigated particle shapes inside biodiesel bus. They found bimodal distribution of particles at 0.2 and 0.5  $\mu\text{m}$ . The particle morphology was described by 14 different shape clusters: square, pentagon, hexagon, heptagon, octagon, nonagon, decagon, agglomerate, sphere, triangle, oblong, strip, line or stick, and unknown, by quantitative order. The square particles were common in the samples. Unlike round and triangle particles which are more, pentagon, hexagon, heptagon, octagon, nonagon, decagon, strip, line or sticks are less ones. The abundance cluster of particles shape were agglomerate. Oberdörster *et al.* [57] found that particles disagglomerate more rapid into singlet particles than carbon black particles of the same primary diameter, which could increased in contact time between the particles and the epithelial surface, would enhance interstitial uptake. In another words, particles disagglomeration effected on the behaviour of nanoparticles.

#### Size distribution

Size distribution is a variety of PM concentration (such as number, surface area, volume and mass particle per air unit volume) towards particle sizes. The particle concentration level would decrease herewith particle size enhancement. When particle size reduced from the micrometre to the nanometre range, the increasing toxicity will be appeared due to the increasing in particle surface area. Akhtar *et al.* [58] investigate the effects of size-fractionated ambient PM on epithelial cells in relation to their physicochemical properties. Concentrated ambient PM was collected on filters for three size fractions: coarse (aerodynamic diameter [AD] 2.5-10  $\mu\text{m}$ ), fine (0.15-2.5  $\mu\text{m}$ ), and quasi-ultrafine (<0.2  $\mu\text{m}$ ), near a busy street in Toronto, Ontario, Canada. The results showed that the combined effects both size and chemical composition



should be considered when explaining PM toxicity. Megido *et al.* [59] analyzed the particulate samples (86.0%) which had a diameter within the 0.1 - 2.5 mm range, 1.8% of them had sizes lower than 0.1 mm 40.2% of the total studied particles were estimated to be inhaled and deposited in the human respiratory tract; 12.3% of these particles would reach the deepest zones, thereby posing a major risk to human health. Dieme *et al.* [60] found that variable concentrations of transition metals (i.e. Fe, Al, Pb, Mn, Zn) and organic compounds (i.e. PAHs) contained in the three PM<sub>2.5</sub> samples which might be confidently involved in a time- and/or dose-dependent toxicity, initiating inflammatory processes.

Size distribution divided into many modes which were a size spectrum (on diameter). Size spectrum were determined by a peak of concentration level was exceeded. Nucleation mode (an average diameter < 0,1 μm) [61] contained a very tiny particle (ultrafine particle) or a new particle nucleation which directly formed from gas phase. The ultrafine particle is the greatest number of particle but they do not significantly contribute to PM mass, despite they have a large surface area [18]. The new particle would increase in size by coagulation and growth process (condensation from gas to particle). Only a certain gases like sulfuric acid, water and several heavy organic gases undergone to condensation, but neither do oxygen and nitrogen molecule. Coagulation and growth process changed particle mode to accumulation mode in an average diameter 0, 1- 2 μm. Some particle was removed by rain, but it couldn't fall down because it was too light. Nucleation mode particles were commonly called fine particle, whereas a coarse particle was > 2 μm in size. A coarse particle was too heavy to quickly occur sedimentation during hours or days. Generally, a fine particle does not evolved by condensation to be a larger size than 1 μm. it could be concluded that a coarse mode particles were derived from emission process [26].

Chatoutsidou *et al.* [62] examined two offices to compare indoor air quality between one and another. One of the office was fully occupied by employee during work hours, and another was unoccupied all the time. They found that human presence during work hours significantly influenced indoor particle in an occupied office, compared out of work hours both number and concentration. Principally, indoor condition was especially influenced by human presence with any activities which emitted particulate matter (diameter > 1 mm) without any new emission source (e.g copying machine). It could be concluded that indoor particles were derived from outdoor sources penetration

Afshar\_Mohajer *et al.* [42] investigated binder jetting printer emission. They measured total VOC and aerosol (10 nm - 10 μm) for 2 hours continuously included mass balance model variation with time to obtain emission rates. The highest emission rate was 205 nm dan 407 nm. The time weight average PM<sub>2.5</sub>, PM<sub>10</sub> and total VOC during 24 hours overed USEPA ambient air quality standards.

Glytsos *et al.* [63] researched several indoor activities that significantly emitted of PM. They found that at the early of the candle burning process, the particulate

emissions were smaller than 50 nm, which signified with more than 85% of total particles. The average maximum concentration was  $2.97 \times 10^5 \pm 1.94 \times 10^5 \text{ #cm}^{-3}$ , and the average maximum total particle concentration was  $3.2 \times 10^5 \pm 2.02 \times 10^5 \text{ #cm}^{-3}$  and  $4.92 \times 10^4 \pm 3.23 \times 10^4 \text{ #cm}^{-3}$  correspondingly. Maximum concentration was identified before closing stages of candle burning process, in contrast to common of other simulated sources in the current study. The source was active at  $376 \pm 176 \text{ μgm}^{-3}$  (the average maximum PM<sub>2.5</sub> mass concentration) and was observed just before the candle was obscured. However at hot plate heating [63] higher dust load on the plate resulted mainly in nano particle emissions since 90% of particles were below 50 nm in the first two experiments. This percentage had dropped between 45% and 65% in the following experiments. The size distribution, when the plate was turned on, was bimodal during the emission, and gradually the size distribution turned to unimodal, while the concentration was declining. While water boiling [63], neither the number particle concentration nor the PM<sub>2.5</sub> mass concentration presented a significant increase during the water boiling experiments. The result of onion frying corresponded at maximum PM<sub>2.5</sub> concentrations ranged between 70 and 600 μgm<sup>-3</sup>, whereas vacuuming obtained that only the number concentration of nano particles increased during this activity and the mean maximum concentration was  $6 \times 10^3 \text{ #cm}^{-3}$ . While hair dryer was observed during the first experiment and 98% of the total particles were nano particles. Hair spray experiment showed that particles larger than 1 μm were mainly emitted at maximum mass concentrations ranged between 580 and 1033 μgm<sup>-3</sup> the PM<sub>2.5</sub> concentration during the experiment that resulted in maximum particle mass concentration. However smoking experiment obtained the average maximum of PM<sub>2.5</sub> mass concentration was  $1200 \times 200 \text{ μgm}^{-3}$ .

## CHEMICAL CHARACTERISTICS

Particulate matters mass concentration alone might not be able to explain the health outcomes, because PM is a non chemically specific. They interact in a complex manner, which supported by PM-size, emission source, atmospheric condition to be induced health effects. Zhang and Balasubramanian [64] observed the Fe in the particles and the changes in chemical composition of particulates are thought to be responsible for the variation of cell viability. Dergham *et al.* [65] found some inorganic, ionic and organic chemical components were preferentially associated with early oxidative events where as others in the later oxidative damage and/or cytokine secretion.

Kelly and Fussel [18] observed chemical composition as a modulator of PM toxicity. They explained the major constituents of PM were soluble secondary inorganic particles (sulphates and nitrates), elemental carbon (black carbon/soot), organic carbon, metals (such as iron (Fe), nickel (Ni), chromium (Cr) and copper (Cu) zinc (Zn), aluminium (Al) and Pb).

Generally, sulphate and nitrate are as aqueous or solid particles or as a surface layer on other solid particles



such as ashes and black carbon, which mainly produced by biological process and vary greatly in strength of acidity. Sometimes, sulphate particle was covered by toxic component such as transition metals or organics material. Lee *et al.* [66] investigated constituent from boiler emission which feed with coal properties. They found that sulphate and elemental carbon were mainly constituent at boiler emission. Lin *et al.* [19] showed that organic carbon, elemental carbon, sulfate, nitrate and ammonium were significantly related with cardiovascular mortality in the experiment with time series model application.

Organic and elemental carbon (also called black carbon or soot) are the greatest fraction of air pollutant, which mainly derived from combustion process, almost up to 80% - 90% of ultrafine particulate mass [67]. Carbonaceous aerosol is commonly derived from biological process and contains secondary organic aerosol formed from the oxidation of biogenic substances (e.g. monoterpene) and anthropogenic (e.g. aromatic) hydrocarbon emission. Organic and elemental carbon have a considerable contribution to particle mass but they showed uncertainties contribution to human health because of their own complexity, heterogeneous nature, which is not well described in geographical setting. More than 200 organic species have been recognized, including alkanes, alkenes, aromatics, oxygenated compounds (including aldehydes, ketones and carboxylic acids), amino compounds, nitrates, polyaromatic hydrocarbons (PAH) and PAH derivatives [68]. Rahman and Kim [69] found benzene, toluene, styrene, methyl ethyl ketone, and butyl acetate were identified in spray product which the risk level exceed the carcinogenic level set for benzene. Dinh *et al.* [70] researched surface coating material from architectural, automotive and marine, and found that surface coating material contained toluene, ethylbenzene, and xylene were the major VOCs.

Metallic component of air pollution were generated from metallurgical process in fuel additives and non-exhaust emissions (like mechanical abrasion such as brake and tyre wear on vehicles). They have a great variation in target of transitional metals such as iron (Fe), V, nickel (Ni), chromium (Cr) and copper (Cu) based on response of biological tissue. Whereas the active metals (such as zinc (Zn), aluminium (Al) and Pb) influenced toxic effects of transition metals to produce free radical [18]. Huang *et al.* [71] investigated the cytotoxicity of PM<sub>2.5</sub> from road dust and air-conditioning (AC) filter dust. They evaluated part the entry of PM<sub>2.5</sub> via ingestion, dermal contact and inhalation, and found that water-soluble components of PM caused human hazard synergically with metal (loid)s. Agarwal *et al.* [36] Observed biodiesel engine and its blends emitted PM which contained of elemental and organic carbon especially polyaromatic hydrocarbons such as crustal and anthropogenic trace metals, sulfates, and nitrates. In spite of biodiesel theory were lower emissions, particularly lower particulate mass emissions and is therefore relatively more environment friendly fuel, being renewable in nature. The complexity effect was caused by largely unpredictable interactions between engine

technology and physical and chemical characteristics of PM.

## CONCLUSIONS

The physicochemical characteristics of PM may exacerbate human health, which is largely influenced by emission source. Disagglomeration particles are rapidly into singlet particles which could increased in contact time between the particles and the human epithelial surface would enhance interstitial uptake. However the chemical constituent is a dominant factor, even though the particles actually interact in a complex manner, which supported by PM-size and atmospheric condition to be induced health effects.

## REFERENCES

- [1] S.E. Chatoutsidou, J. Ondráček, O. Tesar, K. Tørseth, V. Ždímal, M. Lazaridis. 2015. Indoor/outdoor particulate matter number and mass concentration in modern offices, *Build. Environ.* 92: 462-474.
- [2] T.L. Thatcher, D.W. Layton. 1995. Deposition, resuspension and penetration of particles within a residence, *Atmos. Environ.* 29: 1487-1497.
- [3] J. Benítez. 1993. *Process Engineering and Design for Air Pollution Control*.
- [4] T. V Vu, J.M. Delgado-Saborit, R.M. Harrison. 2015. Review: Particle number size distributions from seven major sources and implications for source apportionment studies, *Atmos. Environ.* 122: 114-132.
- [5] L. Morawska, Z. Ristovski, E.R. Jayaratne, D.U. Keogh, X. Ling. 2008. Ambient nano and ultrafine particles from motor vehicle emissions: Characteristics, ambient processing and implications on human exposure, *Atmos. Environ.* 42: 8113-8138.
- [6] I. Myers, R.L. Maynard. 2005. Polluted air--outdoors and indoors. *Occup. Med. (Lond).* 55: 432-8.
- [7] D.G. Karottki, G. Bekö, G. Clausen, A.M. Madsen, Z.J. Andersen, A. Massling, *et al.* 2014. Cardiovascular and lung function in relation to outdoor and indoor exposure to fine and ultrafine particulate matter in middle-aged subjects, *Environ. Int.* 73: 372-381.
- [8] U. Franck, S. Odeh, A. Wiedensohler, B. Wehner, O. Herbarth. 2011. The effect of particle size on cardiovascular disorders - The smaller the worse, *Sci. Total Environ.* 409: 4217-4221.



- [9] U. Ackermann-Liebrich. 2011. Respiratory and Cardiovascular Effects of NO<sub>2</sub> in Epidemiological Studies, in: J.O.B.T.-E. of E.H. Nriagu (Ed.), Elsevier, Burlington. pp. 840-844.
- [10] J. Zhao, Y. Xie, X. Qian, R. Jiang, W. Song. 2010. Acute effects of fine particles on cardiovascular system: Differences between the spontaneously hypertensive rats and wistar kyoto rats, *Toxicol. Lett.* 193: 50-60.
- [11] Z. Dagher, G. Garçon, S. Billet, A. Verdin, F. Ledoux, D. Courcot, *et al.* 2007. Role of nuclear factor-kappa B activation in the adverse effects induced by air pollution particulate matter (PM<sub>2.5</sub>) in human epithelial lung cells (L132) in culture. *J. Appl. Toxicol.* 27: 284-90.
- [12] N.S. Orona, F. Astort, G.A. Maglione, P.H.N. Saldiva, J.S. Yakisich, D.R. Tasat. 2014. Direct and indirect air particle cytotoxicity in human alveolar epithelial cells, *Toxicol. Vitro.* 28: 796-802.
- [13] D. Loomis, Y. Grosse, B. Lauby-Secretan, F. El Ghissassi, V. Bouvard, L. Benbrahim-Tallaa, *et al.* 2013. The carcinogenicity of outdoor air pollution, *Lancet Oncol.* 14: 1262-1263.
- [14] B. Lin, X. Li, H. Zhang, Z. Lin, L. Tian, C. Nie, *et al.* 2014. Comparison of in vitro toxicity of mainstream cigarette smoke particulate matter from nano- to micro-size, *Food Chem. Toxicol.* 64: 353-360.
- [15] T.F. Mar, G.A. Norris, J.Q. Koenig, T. V Larson. 2000. Associations between air pollution and mortality in Phoenix, 1995-1997. *Environ. Health Perspect.* 108: 347-53.
- [16] D.A. Notter. 2015. Life cycle impact assessment modeling for particulate matter: A new approach based on physico-chemical particle properties, *Environ. Int.* 82: 10-20.
- [17] K. Donaldson, F.A. Murphy, R. Duffin, C.A. Poland. 2010. Asbestos, carbon nanotubes and the pleural mesothelium: a review of the hypothesis regarding the role of long fibre retention in the parietal pleura, inflammation and mesothelioma. *Part. Fibre Toxicol.* 7: 5. doi: 10.1186/1743-8977-7-5.
- [18] F.J. Kelly, J.C. Fussell. 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter, *Atmos. Environ.* 60: 504-526.
- [19] H. Lin, J. Tao, Y. Du, T. Liu, Z. Qian, L. Tian, *et al.* 2016. Particle size and chemical constituents of ambient particulate pollution associated with cardiovascular mortality in Guangzhou, China, *Environ. Pollut.* 208, Part, 758-766.
- [20] T. Kouimtzis, C. Samara. 1995. eds., *Airborne Particulate Matter*, Springer Berlin Heidelberg, Berlin, Heidelberg.
- [21] 2003. WHO, Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide, Report on a WHO Working Group, WHO 2003-European Environment Agency.
- [22] 2014. WHO, Health risks of particulate matter from long-range transboundary air pollution.
- [23] C.D. Cooper, F.C. Alley. 2011. *Air Pollution Control: A Design Approach*.
- [24] K.K.R. Mogireddy. 2011. *Physical Characterization of Particulate Matter Employing Support Vector Machine Aided Image Processing*.
- [25] D.A. Vallero. 2007. *Fundamentals of Air Pollution, Fourth Edition*: Daniel Vallero: 9780123736154: Amazon.com: Books, Elsevier.
- [26] M.Z. Jacobson. 2002. *Atmospheric Pollution, History, Science and Regulation*, Cambridge University Press, Cambridge.
- [27] J. Hovorka, M. Braniš. 2011. New particle formation and condensational growth in a large indoor space, *Atmos. Environ.* 45: 2736-2749.
- [28] National Research Council. 2004. *Research Priorities for Airborne Particulate Matter*, National Academies Press, Washington, D.C.
- [29] Y. Huang, K.F. Ho, S.S.H. Ho, S.C. Lee, P.S. Yau, Y. Cheng. 2011. Physical parameters effect on ozone-initiated formation of indoor secondary organic aerosols with emissions from cleaning products, *J. Hazard. Mater.* 192; 1787-1794.
- [30] C.J. Weschler, A.T. Hodgson, J.D. Wooley. 1992. Indoor chemistry: ozone, volatile organic compounds, and carpets, *Environ. Sci. Technol.* 26: 2371-2377.
- [31] H.-L. Huang, T.-J. Tsai, N.-Y. Hsu, C.-C. Lee, P.-C. Wu, H.-J. Su. 2012. Effects of essential oils on the formation of formaldehyde and secondary organic



- aerosols in an aromatherapy environment, *Build. Environ.* 57: 120-125.
- [32] C.P. Hoang, K.A. Kinney, R.L. Corsi. 2009. Ozone removal by green building materials, *Build. Environ.* 44: 1627-1633.
- [33] H. Tse, C.W. Leung, C.S. Cheung. 2015. Investigation on the combustion characteristics and particulate emissions from a diesel engine fueled with diesel-biodiesel-ethanol blends, *Energy*. 83: 343-350.
- [34] A.K. Agarwal, H. Karare, A. Dhar. 2014. Combustion, performance, emissions and particulate characterization of a methanol-gasoline blend (gasohol) fuelled medium duty spark ignition transportation engine, *Fuel Process. Technol.* 121: 16-24.
- [35] F. Di Natale, C. Carotenuto. 2015. Particulate matter in marine diesel engines exhausts: Emissions and control strategies, *Transp. Res. Part D Transp. Environ.* 40: 166-191.
- [36] A.K. Agarwal, T. Gupta, P.C. Shukla, A. Dhar. 2015. Particulate emissions from biodiesel fuelled CI engines, *Energy Convers. Manag.* 94: 311-330.
- [37] Y. Liu, X. Zhou, D. Wang, C. Song, J. Liu. 2015. A prediction model of VOC partition coefficient in porous building materials based on adsorption potential theory, *Build. Environ.* 93, Part 2, 221-233.
- [38] M. Marion, A.L. Tiffonnet, A. Santa-Cruz, R. Makhoulfi. 2011. Study of the resistances to transfer of gaseous pollutant between material and indoor air, *Build. Environ.* 46: 356-362.
- [39] Y.-H. Cheng, C.-C. Lin, S.-C. Hsu. 2015. Comparison of conventional and green building materials in respect of VOC emissions and ozone impact on secondary carbonyl emissions, *Build. Environ.* 87: 274-282.
- [40] C. Yu, D. Crump. 1998. A review of the emission of VOCs from polymeric materials used in buildings, *Build. Environ.* 33: 357-374.
- [41] K. Qian, Y. Zhang, J.C. Little, X. Wang. 2007. Dimensionless correlations to predict VOC emissions from dry building materials, *Atmos. Environ.* 41: 352-359.
- [42] N. Afshar-Mohajer, C.-Y. Wu, T. Ladun, D.A. Rajon, Y. Huang. 2015. Characterization of particulate matters and total VOC emissions from a binder jetting 3D printer, *Build. Environ.* 93, Part 2, 293-301.
- [43] B.J. Mullins, D. Bertolatti, R. Mead-Hunter. 2013. Assessment of polyaromatic hydrocarbon emissions from laser printers, *Atmos. Environ.* 79: 428-432.
- [44] Lazaridis, N. Serfozo, S.E. Chatoutsidou, T. Glytsos. 2015. New particle formation events arising from painting materials in an indoor microenvironment, *Atmos. Environ.* 102: 86-95.
- [45] U.B. Celebi, N. Vardar. 2008. Investigation of VOC emissions from indoor and outdoor painting processes in shipyards, *Atmos. Environ.* 42: 5685-5695.
- [46] G. Buonanno, L. Morawska, L. Stabile. 2009. Particle emission factors during cooking activities, *Atmos. Environ.* 43: 3235-3242.
- [47] C.J. Weschler. 2004. Chemical reactions among indoor pollutants: what we've learned in the new millennium, *Indoor Air*. 14 Suppl 7: 184-94. doi:10.1111/j.1600-0668.2004.00287.x.
- [48] Y. Cheng, C.-C. Lin, S.-C. Hsu. 2015. Comparison of conventional and green building materials in respect of VOC emissions and ozone impact on secondary carbonyl emissions, *Build. Environ.* 87: 274-282.
- [49] H. Wang, G.C. Morrison. 2006. Ozone-initiated secondary emission rates of aldehydes from indoor surfaces in four homes, *Environ. Sci. Technol.* 40: 5263-8.
- [50] L. Wallace. 2006. Indoor Sources of Ultrafine and Accumulation Mode Particles: Size Distributions, Size-Resolved Concentrations, and Source Strengths, *Aerosol Sci. Technol.* 40: 348-360.
- [51] R.B. Lamorena, W. Lee. 2008. Influence of ozone concentration and temperature on ultra-fine particle and gaseous volatile organic compound formations generated during the ozone-initiated reactions with emitted terpenes from a car air freshener, *J. Hazard. Mater.* 158: 471-477.
- [52] S. Langer, J. Moldanová, K. Arrhenius, E. Ljungström, L. Ekberg. 2008. Ultrafine particles produced by ozone/limonene reactions in indoor air under low/closed ventilation conditions, *Atmos. Environ.* 42: 4149-4159.
- [53] Y. Huang, S.C. Lee, K.F. Ho, S.S.H. Ho, N. Cao, Y. Cheng, *et al.* 2012. Effect of ammonia on ozone-



- initiated formation of indoor secondary products with emissions from cleaning products, *Atmos. Environ.* 59: 224-231.
- [54] P. Rounce, A. Tsolakis, A.P.E. York. 2012. Speciation of particulate matter and hydrocarbon emissions from biodiesel combustion and its reduction by aftertreatment, *Fuel*. 96: 90-99.
- [55] A.M. Backes, A. Aulinger, J. Bieser, V. Matthias, M. Quante. 2016. Ammonia emissions in Europe, part II: How ammonia emission abatement strategies affect secondary aerosols, *Atmos. Environ.* 126: 153-161.
- [56] K.K. Shandilya, A. Kumar. 2010. Morphology of single inhalable particle inside public transit biodiesel fueled bus, *J. Environ. Sci.* 22: 263-270.
- [57] G. Oberdörster, J. Ferin, P.E. Morrow. 1992. Volumetric loading of alveolar macrophages (AM): a possible basis for diminished AM-mediated particle clearance. *Exp. Lung Res.* 18: 87-104.
- [58] U.S. Akhtar, N. Rastogi, R.D. McWhinney, B. Urch, C.-W. Chow, G.J. Evans, *et al.* 2014. The combined effects of physicochemical properties of size-fractionated ambient particulate matter on in vitro toxicity in human A549 lung epithelial cells, *Toxicol. Reports*. 1: 145-156.
- [59] L. Megido, B. Suárez-Peña, L. Negral, L. Castrillón, S. Suárez, Y. Fernández-Nava, *et al.* 2016. Relationship between physico-chemical characteristics and potential toxicity of PM10, *Chemosphere*. 162: 73-79.
- [60] D. Dieme, M. Cabral-Ndior, G. Garçon, A. Verdin, S. Billet, F. Cazier, *et al.* 2012. Relationship between physicochemical characterization and toxicity of fine particulate matter (PM2.5) collected in Dakar city (Senegal), *Environ. Res.* 113: 1-13.
- [61] T. Hussein, K. Hämeri, M.S.A. Heikkinen, M. Kulmala. 2005. Indoor and outdoor particle size characterization at a family house in Espoo–Finland, *Atmos. Environ.* 39: 3697-3709.
- [62] S.E. Chatoutsidou, J. Ondráček, O. Tesar, K. Tørseth, V. Ždimal, M. Lazaridis. 2015. Indoor/outdoor particulate matter number and mass concentration in modern offices, *Build. Environ.* 92: 462-474.
- [63] T. Glytsos, J. Ondráček, L. Džumbová, I. Kopanakis, M. Lazaridis. 2010. Characterization of particulate matter concentrations during controlled indoor activities, *Atmos. Environ.* 44: 1539-1549.
- [64] Z.-H. Zhang, R. Balasubramanian. 2015. Influence of an iron-based fuel-borne catalyst on physicochemical and toxicological characteristics of particulate emissions from a diesel engine, *Appl. Energy*. 146: 270-278.
- [65] M. Dergham, C. Lepers, A. Verdin, F. Cazier, S. Billet, D. Courcot, *et al.* 2015. Temporal–spatial variations of the physicochemical characteristics of air pollution Particulate Matter (PM2.5-0.3) and toxicological effects in human bronchial epithelial cells (BEAS-2B), *Environ. Res.* 137: 256-267.
- [66] S. Win Lee, T. Herage, R. Dureau, B. Young. 2013. Measurement of PM2.5 and ultra-fine particulate emissions from coal-fired utility boilers, *Fuel*. 108: 60-66.
- [67] J. Heintzenberg. 1989. Fine particles in the global troposphere A review, *Tellus B*. 41.
- [68] J.H. Seinfeld, S.N. Pandis. 1998. Atmospheric chemistry and physics: from air pollution to climate change..
- [69] M.M. Rahman, K.-H. Kim. 2014. Potential hazard of volatile organic compounds contained in household spray products, *Atmos. Environ.* 85: 266-274.
- [70] T.-V. Dinh, I.-Y. Choi, Y.-S. Son, K.-Y. Song, Y. Sunwoo, J.-C. Kim. 2016. Volatile organic compounds (VOCs) in surface coating materials: Their compositions and potential as an alternative fuel, *J. Environ. Manage.* 168: 157-164.
- [71] M. Huang, Y. Kang, W. Wang, C.Y. Chan, X. Wang, M.H. Wong. 2015. Potential cytotoxicity of water-soluble fraction of dust and particulate matters and relation to metal (loid) s based on three human cell lines, *Chemosphere*. 135: 61-66.