Pertanika J. Sci. & Technol. 28 (S1): 1 - 13 (2020)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

Conceptual Framework - Hazard Assessment of Nanomaterials Using Bayesian Network

Mardhati Zainal Abidin, Risza Rusli* and Norsuzieanah Halil

Centre of Advanced Process Safety, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia

ABSTRACT

The development and application of advanced materials i.e. nanomaterials are important for the technology revolution and economic progress of the country. However, the potential health risk arising from nanomaterials become a major concern. Given the fact that both particulate and molecular identity of nanomaterials is responsible for the biological effects, the effects of nanomaterial exposure cannot be predicted based on the current understanding of their bulk properties. The lack of nanomaterials data for safety assessment become a major challenge to implement safe work practice at nanomaterials related industries. To resolve the aforementioned problem, a conceptual framework for hazard assessment of nanomaterials is presented in this study. Bayesian Network (BN) is used to support hazard assessment according to the guideline issued by the Department of Occupational Safety and Health (DOSH) Malaysia. The understanding of the hazard is crucial to encourage the development of an action plan to ensure the safety aspect while processing and handling nanomaterials.

Keywords: Bayesian Network, big data, data-driven, nanomaterials risk, prediction

ARTICLE INFO

Article history:
Received: 26 February 2020
Accepted: 18 May 2020
Published: 16 September 2020

E-mail addresses:
mardhati.zainal@utp.edu.my (Mardhati Zainal Abidin)
risza@utp.edu.my (Risza Rusli)
suzyanahalil@gmail.com (Norsuzieanah Halil)
*Corresponding author

INTRODUCTION

The development and application of advanced materials which are nanomaterials are important for the technology revolution and economic growth around the world. At the scale of 1 to 100 nanometers, nanomaterials pose unique physical, chemical, and biological properties. The surface and quantum effect of nanoscale

ISSN: 0128-7680
e-ISSN: 2231-8526

materials give a significant influence on the behaviours. The quantum effects will affect the optical, electrical, thermal, mechanical and magnetic properties while surface effects will affect the reactivity (Azoulay et al., 2013). These properties can improve the performance and characteristics of the final products. Therefore, they have been widely used in different sectors such as construction, energy storage, electric and electronic, paint and coating, and food agricultural. The database from STATNANO indicates the vast usage of nanomaterials around the world involving 2237 companies from 60 countries.

Market Overview and Consumers Perception

Due to the vast industrial application, the nanomaterials market is booming in recent years with a promising market value worldwide. According to the report by Inkwood Research, the market was valued $14,741.6 million in 2015 and is expected to reach $55,016 million by 2022, supported by a compound annual growth rate (CAGR) of 20.7% (Inkwood Research, 2017). In Malaysia, the government plays a prominent role in the advancement of nanomaterials technologies by supporting research and development, pre-commercialization, scale-up, and commercialization process, providing the fund valued at MYR176.3 million in 9th,10th and 11th Malaysia Plan until June 2016. Further, RM 75 million and MYR10.9 million funds were allocated for Graphene Commercialization and Nanosafety Risk Level Determination project respectively (Masrom, 2016). National Nanotechnology Centre (NNC) was established in 2010 under the Ministry of Science, Technology, and Innovation (MOSTI) as a national focal point to manage all activities related to nanomaterials in Malaysia. Under the National Policy on Industry 4.0, the nanomaterials-related activities are anticipated to become one of the new economic drivers for Malaysian industries (MITI, 2018). According to the report by MIMOS Berhad, the advancement in nanotechnology in the electric and electronic sector is expected to raise the sector by 20% to 30% in 2020 (MIMOS Berhad, 2015). The activation of graphene projects by NanoMalaysia in March 2018 was expected to generate a future revenue of RM1.35 billion and could potentially achieve RM20 billion in gross national income (GNI) impact (Ong, 2018).

While a great advancement of nanomaterials in the industry can be observed, public perceptions and their acceptances play important roles and become key in determining the future of nanotechnology. A survey done in Malaysia involving 512 tertiary students shows that 14.06% of the respondents know about nanomaterials and 75.97% of them have heard the word ‘nanotechnology’. Overall, the respondents have a positive impression of nanotechnology (Karim et al., 2017). A survey conducted in South Korea involving 1007 consumers indicated low awareness about nanotechnology among them in which 80.3% of respondents did not know about nanotechnology. Although they were concern about safety status, they had a positive impression of nanotechnology. According to the study, the respondents who come from low household income have low awareness about nanotechnology (Lee et al., 2005). Another study conducted in the same region showed that the experts had a higher level of awareness about nanotechnology than consumers. The experts had a concern about the safety issue and they perceived the nanotechnology negatively (Kim et al., 2014b). A survey done in Singapore involving 1,080 consumers indicated a high level of awareness among the younger generation and educated people and they had a concern about the safeness of nanomaterials in food and medicine (George et al., 2014). A study conducted in the United State of America (USA) also showed a similar finding whereby younger and educated people were aware of nanotechnology. By contrast, the European people are less optimistic compared to USA respondents in which they have a concern about the impact of technology on the environment and lack of confidence towards the regulatory body. Different perceptions in these two regions were influenced by media coverage, where the potential benefits of nanotechnology were highlighted more in the USA than in the United Kingdom (UK) (Gaskell et al., 2004). The fact that the younger and educated respondents react negatively towards nanotechnology shows that they are aware of the potential risk that comes from nanomaterials products. However, the uncertainty in risk information will instil unnecessary fear that may lead to rejection. Therefore, the clarity and the right information are very crucial in shaping the perception of risks versus benefits of nanotechnology and general attitudes toward nanotechnology.

Safety Issue

Nanomaterials Safety Issue and Previous Developed Tools. The rapid growth of the nanomaterials industry gives a good prospect for employment whereby in 2020, around 6 million workforces will be employed worldwide (Roco, 2011). However, the lack of information regarding nanomaterials leads to the lack of understanding related to the occupational, health and safety aspects. This issue will contribute to the negligence towards safe work practice in which workers will exposed the to the danger. The previous studies reported that most of the nanomaterials were produced mainly by small businesses (Azoulay et al., 2013). For the manufacturing process, the business with sales turnover between RM300,000 to RM15,000,000 or the number of employees between 5 to 75 are classified as a small business (SME Corporation Malaysia, 2013). Comparing with the major hazard installation such as oil and gas industries that are bound to comply with safety regulations such as Process Safety Management (PSM) or Control of Major Accident Hazards (COMAH), the occupational safety level for small businesses are relatively poor.

According to the previous studies, the exposure of nanoparticles, especially through inhalation, may give a negative impact on human health. Previously reported cases due to the exposure of nanoparticles are summarized in Table 1. Among the challenges to ensure the safety aspect for the process involving nanomaterials is the lack of nanomaterials data for safety assessment. Given the fact that both particulate and molecular identity of nanomaterials are responsible for the biological effects, the effects of nanomaterials exposure cannot be predicted based on the current understanding of their bulk properties. Therefore, different groups of researchers highlighted the need of identifying the risk of nanomaterials towards humans and environments to develop the precautionary approach for nanomaterials risk (Azoulay et al., 2013; Karim et al., 2017; Kim et al., 2014a; Yokel & MacPhail, 2011). However, with the conventional way to collect the data through lab testing, the industries facing a great challenge to keep pace with the high speed of the development that results in an ever-increasing diversity of nanomaterials in industry. Further, the conventional lab testing methods are time-consuming, involving the high cost of experimental equipment, breach the ethical and suffer from inaccuracy on the results.

Table 1
Previous reported cases on nanomaterials exposure

Source	Activity / process	Syndrome	Consequence	Evidence
Phillips et al. (2010); Rendall et al. (1995)	Spraying nickel in a metal arc process	Respiratory distress syndrome	One fatality	• High level of nickel found in urine and kidney • Nanoparticles with the size less than 25 nm found in alveolar macrophages
Hull and Abraham (2002)	Aluminum welding	Pneumoconiosis	Two fatalities	• Aluminum concentration from 8.5 to 11.2 billion particles per cm3 of lung tissue. Most of the particles have 10 nm in size
Song et al. (2011, 2009)	Polyacrylate spray painting	Shortness of breath, pleural effusion, progressive pulmonary fibrosis	Seven injuries	• Silica nanoparticles in alveolar macrophages, epithelial cells, and chest fluid
Cheng et al. (2012)	Polyester powder painting	Bronchiolitis obliterans organizing pneumonia	One fatality	• Titanium dioxide nanoparticles in pulmonary sample

Table 1 *(Continued)*

Source	Activity / process	Syndrome	Consequence	Evidence
Theegarten et al. (2010)	Toner from the laser printing process	Abdominal pain, weight loss, and diarrhea	One injury	• Submesothelial aggregates of carbon nanoparticle (CNP) with a diameter of 31-67 nm were found in tissue specimens
Kim and Yu (2016)	340 workplaces handling or manufacturing nanomaterials	Suspected respiratory occupational disease	Nine injuries	• Not specify
		Recommended for regular follow-up health monitoring	Seven injuries	

To resolve this issue, several research groups developed the computerized tools for risk assessment as summarized in Table 2. Although the proposed tools are useful, these tools should be used with care. A comparison study done by Jiménez et al. (2016) shows that the assessment done using the tools as in Table 2 gave different outcomes, which were contributed by several factors; limitation on the activities covered by the tools, the dependency on expert judgment due to the lack of data, high sensitivity towards the changes in exposure input data but lack of sensitivity to the changes of hazard (Jiménez et al., 2016).

Table 2

Computerized tools for nanomaterials risk assessment (Jiménez et al., 2016)

Tools	Developer	Description
NanoSafer	National Research Centre for the Working Environment (NRCWE), Denmark	• Assess exposure and hazard when handling powders in the case of spills. • The tool provides a risk evaluation in the near and far-field for short (15min) and long-term (8hrs) exposure. • Estimates whether the material is nano-relevant from the input parameters (i.e. particles less than or equal to 200 nm and or products with a specific surface area more than or equal to $30m^2g^{-1}$

Table 2 *(Continued)*

Tools	Developer	Description
CB Nano Tool	Lawrence Livermore National Laboratory in the United States	The tool estimates an emission probability (without considering exposure controls) and severity band and provides advice on engineering controls to use. Includes nine domains covering the handling of liquids, powders, and abrasion of solids. The tool does not make any assessment of whether the substances are nano-relevant based on the substance's input parameters.
Stoffenmanager-Nano	The consortium led by TNO, Netherlands	Estimating an exposure and hazard band, providing a risk prioritization and recommending a series of control measures Four domains are considered: synthesis, powder handling, spray and dispersions of ready to use nanoproducts, fracturing, and abrasion of nanomaterials embedded in products The substance of nano-relevant (defined as particle size less than 100nm and/or products with a specific surface area more than or equal to $60m^2g^{-1}$ No reference is made to the substance's input parameters
The Precautionary Matrix	TEMAS Switzerland	Provide advice about whether a precautionary approach is required under normal working conditions, worst scenario and for the environment. Assesses the nano-relevance of the substance as a function of the particle diameter and the solubility in the lung
Nanotoolkit	California Nanosafety Consortium of Higher Education	Provide practical guidance as to how nanomaterials should be handled safely in the research laboratory setting

In the process safety area, the causal relationships between parameters can be used to enhance the understanding of the process. Among the common technique used in process safety is fault tree analysis (FTA). FTA is a technique for identifying and analyzing factors that can contribute to a specified undesired event (called the “top event”) based on the causal factors e.g. component hardware failures and human errors. FTA can be used to identify potential causes and pathways to failure (the top event) or to calculate the probability of the top event, given knowledge of the probabilities of causal events. The FTA has been used in ARAMIS Project for MIMAH and MIRAS methodology by Delvosalle (Delvosalle et al., 2006). Although it has been used extensively in process safety, FTA is not suitable for analyzing large systems, especially for the system with redundant failures, common cause failures, or mutually exclusive primary events. Further, the assumption used in FTA where the events are assumed independent is invalid (Khakzad et al., 2011). In recent years, a Bayesian network (BN) methodology has begun to be used in engineering applications. A BN is a graphical inference technique used to express the causal relationships among variables. BNs are used either to predict or to update the probability of known variables given the certain state of other variables (evidence) through the process of probability propagation or reasoning. The reasoning is based on Bayes' theorem. BN is ideal for taking an event that occurred and predicting the likelihood of several possible known causes was the contributing factor. The capability of BN to perform three inference tasks; inferring unobserved variables, parameter learning, and structure learning make BN become a promising technique for process safety (Khakzad et al., 2011).

Due to the advantages offered by BN, BN was used in this work for the prediction of hazard potential due to nanomaterials exposure. A new framework is proposed in this study by integrating the BN output with the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018). The strength of the framework:

- The graphical model from BN is very important to enhance the understanding of the interdependency between exposure routes, potential biological effects and physicochemical properties of nanomaterials.
- The data-driven technique in BN is used for hazard prediction whereby the machine learning algorithm will be used to resolve the lack of nanomaterials data for safety assessment. This is a very important feature that can contribute to the time efficiency, reduction of manpower, and cost-effectiveness.
- Further, the integration of BN to support the hazard assessment process based on the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) is valuable as a widely accepted guideline is used for the Malaysian process industries.

Conceptual Framework and Expected Results

Figure 1 summarizes the flowchart of the proposed framework followed by brief explanations of each activity.

Understand the Process and Identification of the Group of Hazard. The first step in this work is to understand the process and identification of the group of hazards. To complete the step, the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) is used as guidance. The nature of the process needs to be understood; the process/task and work activities involving nanomaterials, the degree of release, the exposure duration, and the hazard group. The process/task and work activities divided into production of nanomaterials, downstream processing, product packaging, and maintenance. From the process/task and work activities, the potential nanomaterials exposure can be identified. Subsequently, the degree of release needs to be identified based on the state:

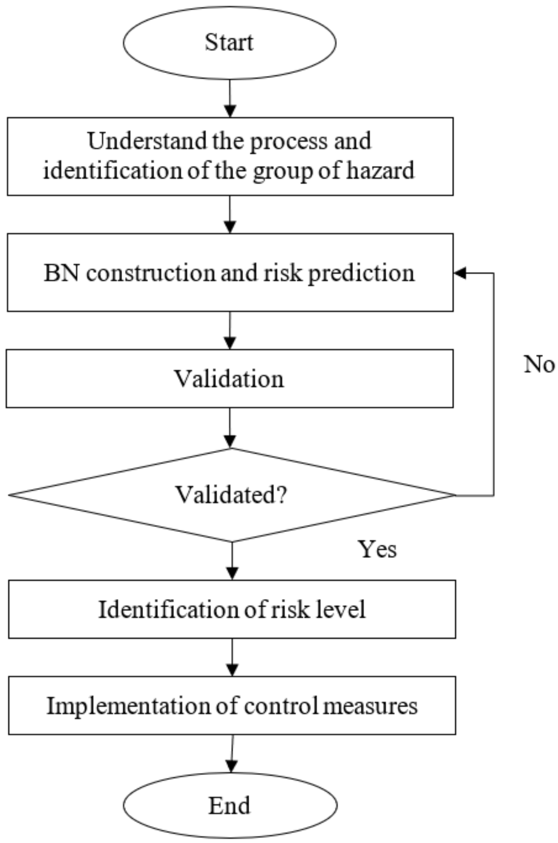

Figure 1. Conceptual framework of nanomaterial risk assessment

bound, potential and free/unbound. The exposure duration needs to be categorized based on three categories; short (4hours/day or 2days/week), medium (4 to 6 hours/day or 3 to 5 days/week) and long (6 to >8hours/day or 3 to 5 days/week). The hazard group needs to be identified from Group A (known to be inert), Group B (understand reactivity and function) and Group C (unknown properties). Based on the above criteria, the rating of the process involving nanomaterials will be given based on guidance from the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) in Table 3. In the next step, the BN model will be developed to further understand the risk of nanomaterials.

Table 3

Risk level of nanomaterial exposure

Degree of Release Exposure duration	Bound material	Potential release	Free/unbound
Hazard Group A (known to be inert)			
Short	1	1	2

Table 3 *(Continued)*

Degree of Release Exposure duration	Bound material	Potential release	Free/unbound
Hazard Group A (known to be inert)			
Medium	1	1	2
Long	1	2	2
Hazard Group B (understand reactivity/function)			
Short	1	2	2
Medium	1	2	3
Long	1	3	3
Hazard Group C (unknown properties)			
Short	2	2	3
Medium	2	3	4
Long	2	4	4

BN Construction and Risk Prediction. In this work, GeNIe Modeler from BayesFusion (2019) is used to re-construct the BN model using the data from previous research work by Marvin et al. (2017). The data has been classified in the group as presented in Table 4. The main purpose of model development in this work is to capture the interdependency between exposure routes, potential biological effects, and physicochemical properties. The initial BN graphical structure is constructed manually. Subsequently 467 nanomaterials data are used for parameter learning for each node to produce an optimal configuration. The optimal configuration is produced via the interaction between nodes and with sufficient data, the machine learning algorithm (expectation-maximization algorithm) embedded in this software can estimate the conditional probability table (CPT).

Table 4

Classification of nanomaterials

Exposure routes	Physicochemical properties	Potential biological effects
Inhalation	Shape	Cytotoxicity
Oral	Purity of nanomaterials	Neurological effects
Dermal	Dissolution	Pulmonary effects
Intravenous	Surface area	Fibrosis
	Surface charge	RCNS effects
	Surface coatings	Immunological effects
	Surface reactivity	Genotoxicity
	Aggregation	Inflammation
	Particle size	

BN is a graphical model that represents a probabilistic relationship among a set of nodes (Figure 2). The nodes represent the variables U = {A_i, ..., A_n} and the directed links between them indicate the relationship among the nodes. Each node is composed of a set of states. A node A_i is the parent of the child node A_j, if there is a link from A_i to A_j. BN specifies a unique joint probabilistic distribution of all nodes P(U) = P(A_1, ..., A_n), given by the product of all conditional probabilistic tables specified in BN:

$$P(U) = \prod_{i=1}^{n} P(A_i \mid pa(A_i))$$

where pa(A_i) are parents of node A_i and P(A_i|pa(A_i)) specifies a conditional probabilistic distribution. The calculations are based on Bayesian theory, where the probabilistic of event A at the condition of event B is expressed as:

$$P(A \mid B) = \frac{P(B \mid A) \times P(A)}{P(B)}$$

In which P(A) is the prior probability of A, P(B|A) is the probabilistic of B under the condition of a known event A and P(B) is prior probabilistic of B. An example of BN with six nodes is shown in Figure 2. The corresponding decomposition of the joint distribution of nodes is given by:

$$P(A_1,\ldots,A_6) = P(A_1)P(A_2)P(A_3)P(A_4 \mid A_1, A_2)P(A_5 \mid A_2, A_3)P(A_6 \mid A_4, A_5).$$

To calculate the joint distribution, unconditional distributions of $P(A_1), P(A_2), P(A_3)$ and conditional distributions $P(A_4 \mid A_1, A_2)P(A_5 \mid A_2, A_3)P(A_6 \mid A_4, A_5)$ should be specified. The nanomaterials hazard will be classified into four different categories which are none, low, medium, and high. The highest predicted probability become the indicator on the category of hazard.

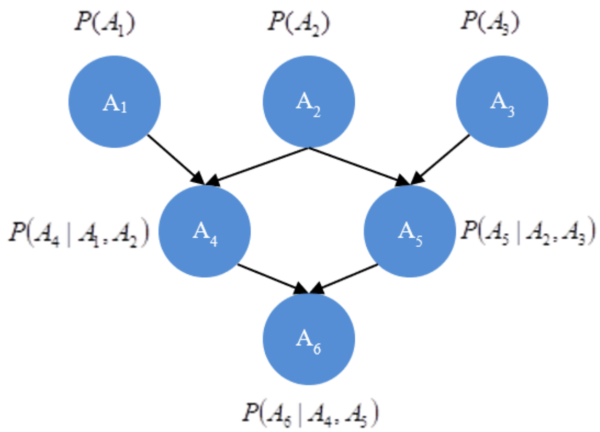

Figure 2. An example of a Bayesian Network showing the relationship between a set of nodes

Validation. The validation of the BN model is performed using the K-fold cross-validation method in which divides the data set into K parts of equal size, trains the network on K-1 parts, and tests it on the last, K^{th} part. The process is repeated K times, with a different part of the data being selected for testing. The accuracy, the confusion matrix, the Receiver Operating Characteristic (ROC) curve and calibration curve are monitor and observe to ensure the developed BN model can predict the hazard accurately. The diagonal cells in the confusion matrix will show the numbers of correctly identified instances for each of the classes and off-diagonal cells show incorrectly identified classes. The ROC curves for each of the states of each of the class variables indicate the quality of a model-independent of the classification decision. Calibration curve comparing the output probability to the observed frequencies in the data to measure the accuracy of a model (BayesFusion, 2019).

Implementation of Control Measures. In this work, the control band key is identified according to the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) as shown in Table 5. The probability obtained from the BN model is used to support and detailed out the control measure identified from Table 5. The results are very useful in improving understanding and hazard management strategies.

Table 5
Control band key

Band	Control measures
1	General ventilation and personal protective equipment (PPE)
2	Engineering controls and/or respirators, additional PPE
3	Containment (e.g. glove box)
4	Seek specialist advice

CONCLUSION

In this study, a conceptual framework for hazard assessment has been proposed by combining BN into the risk assessment guidelines proposed by DOSH. The implementation of the BN in this framework is very important for prediction purposes to resolve the data limitation issue for nanomaterials. By having this technique, the understanding of the risk can be improved and subsequently can encourage the development of an action plan to ensure the safety aspect while processing and handling nanomaterials. The implementation of the proposed framework to assess nanomaterials risk will be demonstrated in future work.

ACKNOWLEDGEMENT

This study is funded by National Institute of Occupational Safety And Health (NIOSH) Malaysia under the grant " Prediction of Nanomaterials Risk Using Bayesian Network".

REFERENCES

Azoulay, D., Senjen, R., & Foladori, G. (2013). Social and environmental implications of nanotechnology development in Asia-Pacific. Gothenburg, Sweden: IPEN.

BayesFusion, LLC. (2019). *GeNIe Modeler User Manual Version 2.4.R1.* Pittsburgh, Pennsylvania. Retrieved January 5, 2020, from https://support.bayesfusion.com/docs/

Cheng, T. H., Ko, F. C., Chang, J. L., & Wu, K. A. (2012). Bronchiolitis obliterans organizing pneumonia due to titanium nanoparticles in paint. *The Annals of Thoracic Surgery, 93*(2), 666–669.

Delvosalle, C., Fievez, C., Pipart, A., & Debray, B. (2006). ARAMIS project: A comprehensive methodology for the identification of reference accident scenarios in process industries. *Journal of Hazardous Materials, 130*(3), 200–219.

DOSH. (2018). *Guideline on control and safe handling of nanomaterials 2018*. Putrajaya, Malaysia: Department of Occupational Safety and Health, Ministry of Human Resource Malaysia.

Gaskell, G., Eyck, T. T., Jackson, J., & Veltri, G. (2004). Public attitudes to nanotech in Europe and the United States. *Nature Materials, 3*(8), 496-496.

George, S., Kaptan, G., Lee, J., & Frewer, L. (2014). Awareness on adverse effects of nanotechnology increases negative perception among public: Survey study from Singapore. *Journal of Nanoparticle Research, 16* (12), 1-11.

Inkwood Research. (2017). *Global nanomaterials market forecast 2017-2024*. Retrieved December 10, 2019, from https://www.inkwoodresearch.com/reports/global-nanomaterials-market-forecast/#report-summary

Hull, M. J., & Abraham, J. L. (2002). Aluminum welding fume-induced pneumoconiosis. *Human Pathology, 33* (8), 819-825.

Jiménez, A. S., Varet, J., Poland, C., Fern, G., Hankin, S., & van Tongeren, M. (2016). A comparison of control banding tools for nanomaterials. *Journal of Occupational and Environmental Hygiene, 13*(12), 936-949.

Karim, M. E., Akhter, S., Munir, A. B., Muhammad-Sukki, F., Hoque, K. E., Yasin, S. H. M., ... & Mas'ud, A. A. (2017). Malaysian tertiary level students and their understanding, knowledge and perception of nanotechnology. *Journal of Advanced Research in Social and Behavioural Sciences, 6*(1), 52-67.

Khakzad, N., Khan, F., & Amyotte, P. (2011). Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. *Reliability Engineering and System Safety, 96*(8), 925–932.

Kim, J., & Yu, I. J. (2016). National survey of workplaces handling and manufacturing nanomaterials, exposure to and health effects of nanomaterials, and evaluation of nanomaterial safety data sheets. *BioMed Research International, 2016*, 1-10.

Kim, Y. R., Lee, E. J., Park, S. H., Kwon, H. J., An, S. S. A., Son, S. W., … & Kim, M. K. (2014a). Interactive survey of consumer awareness of nanotechnologies and nanoparticles in consumer products in South Korea. *International Journal of Nanomedicine, 9*(Suppl 2),11-20.

Kim, Y. R., Lee, E. J., Park, S. H., Kwon, H. J., An, S. S. A., Son, S. W., … & Kim, M. K. (2014b). Comparative analysis of nanotechnology awareness in consumers and experts in South Korea. *International Journal of Nanomedicine, 9*(Suppl 2), 21–27.

Lee, C., Scheufele, D., & Lewenstein, B. (2005). Public attitudes toward emerging technologies. *Science Communication, 27*(2), 240-267.

Marvin, H. J. P., Bouzembrak, Y., Janssen, E. M., van der Zande, M., Murphy, F., Sheehan, B., & Bouwmeester, H. (2017). Application of bayesian networks for hazard ranking of nanomaterials to support human health risk assessment. *Nanotoxicology, 11*(1), 123–133.

Masrom, A. K. (2016). *National nanotechnology activities and development program*. Retrieved December 10, 2019, from http://www.rmc.upm.edu.my/dokumen/PTPPY1_Slide_Country_Report_Malaysia.pdf

MIMOS Berhad. (2015). *Nanotechnology poised to be new economic driver*. Press Release. Retrieved December 10, 2019, from http://www.mimos.my/wp-content/uploads/2016/09/Nano.pdf

MITI. (2018). *National industry 4.0 policy framework*. Putrajaya, Malaysia: Ministry of International Trade and Industry.

Ong, S. (2018, October 30). Graphene products to contribute RM20b to Malaysia's GNI via action plan. *The Malaysian Reserve*. Retrieved June 24, 2019, from https://themalaysianreserve.com/2018/10/30/graphene-products-to-contribute-rm20b-to-malaysias-gni-via-action-plan/

Phillips, J. I., Green, F. Y., Davies, J. C. A., & Murray, J. (2010). Pulmonary and systemic toxicity following exposure to nickel nanoparticles. *American Journal of Industrial Medicine, 53*(8), 763–767.

Rendall, E.G., Phillips, R., & Renton, K. A. (1995). Death following exposure to fine particulate nickel from a metal. *The Annals of Occupational Hygiene, 38*(6), 921–930.

Roco, M. C. (2011). The long view of nanotechnology development: The national nanotechnology initiative at 10 years. *Journal of Nanoparticle Research, 13*(2), 427–445.

SME Corp. Malaysia. (2013). *Guideline for new SME definition*. Putrajaya, Malaysia: National SME Development Council

Song, Y, Li, X., & Du, X. (2009). Exposure to nanoparticles is related to pleural effusion, pulmonary fibrosis and granuloma. *European Respiratory Journal, 34*(3), 559–567.

Song, Y., Li, X., Wang, L., Rojanasakul, Y., Castranova, V., Li, H., & Ma, J. (2011). Nanomaterials in humans: Identification, characteristics, and potential damage. *Toxicologic Pathology, 39*(5), 841-849.

STATNANO. (n.d.). *Nano science, technology and industry information*. Retrieved June 7, 2019, from https://statnano.com/

Theegarten, D., Boukercha, S., Philippou, S., & Anhenn, O. (2010). Submesothelial deposition of carbon nanoparticles after toner exposition: case report. *Diagnostic Pathology, 5*(1), 1-4.

Yokel, R. A., & MacPhail, R. C. (2011). Engineered nanomaterials: Exposures, hazards, and risk prevention. *Journal of Occupational Medicine and Toxicology, 6*(1), 1-27.