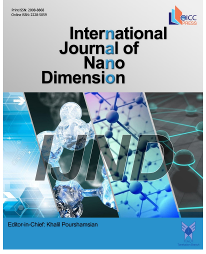

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Original Research

Development of a Health Risk Management Framework in Workplaces Handling Nanomaterials Using Multi-Criteria Decision-Making Methods

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Abstract:

This study developed a comprehensive framework for assessing and managing health risks of manufactured nanomaterials (MNM) in workplaces. The approach combined control banding with multi-criteria decision-making, informed by expert input and a literature review on MNM hazards. A three-layered risk assessment was applied: hazard banding using the Globally Harmonized System (GHS) for five toxic endpoints, exposure banding based on MNM physical state, manufacturing processes, and working conditions (yielding four bands), and integration via control banding to classify risk into five levels. These layers complement each other to enhance accuracy. Control measures were identified and evaluated using a General Technique for Evaluating Control Measures (GTECM), scoring effectiveness, cost, and feasibility, with acceptable inter-rater reliability. The framework was implemented as an online tool to support practical application in Iranian nanotechnology workplaces. Field testing in selected facilities demonstrated its usability and consistency. By systematically integrating hazard, exposure, and control data, the framework supports informed decision-making for occupational health and safety managers. It aims to strengthen risk management practices and promote safer handling of MNMs, contributing to improved workplace health in Iran's growing nanotechnology sector.

Keywords: Health risk; Multi-criteria decision making; Nanomaterials; Occupational exposure; Risk management

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1. Introduction

Nanotechnology employs investigation, conceptualization, and the production of substances, equipment, and frameworks to enable the utilization of manufactured (MNM) or engineered nanomaterials (ENM) across diverse domains, including industry and healthcare, owing to their distinct characteristics and uses [1, 2, 3].

Due to their super small size and higher reactivity, nanomaterials can pass through the respiratory tract, enter the circulatory system and cause inflammation [4]. Nanomaterials may endanger human health through cellular, genetic, sensitivity, inflammation and even carcinogenicity [5, 6].

Although, uncertainties related to the potential hazards of manufactured nanomaterials for human health may have a negative effect on growth expectations [7, 8]. However, there is no detailed information on the effects of nanomaterial exposure to human health due to the limited toxicity data and the measurement methods, for example in the case of carbon nanotubes and titanium dioxide nanoparticles. Therefore, quantitative and rational risk assessment methods of chemical substances can't apply for nanomaterials, appropriately [9]. Currently, there is insufficient information to determine the occupational exposure limits (OELs) for many manufactured nanomaterials (See Fig A1.) [10, 11].

Identifying potential risks, evaluation and decision-making regarding the control measures, requires a detailed risk management approach for manufactured nanomaterials [12]. Risk assessment of chemicals in the workplace begins with the accumulation of information from the potential risk characteristics. This process leads to the evaluation of hazard and exposure. Therefore, the characterization of risk assessment includes the integration of hazard and exposure data (See Table A1).

Based on a systematic approach, it is possible to use the available information for the classification of nanomaterials' occupational risks according to their hazard characteristics and exposure probability. These classifications can facilitate the development of techniques for applying the method for risk assessment and management, such as Control Banding. Control Bonding is an internationally recognized method that not only defines risk levels, but also provides recommendations on selecting control measures for mitigating risks, such as ventilation, personal protective equipment, etc. [13]. In this regard, various tools have been developed as a mean to facilitate risk assessment and risk management of nanomaterials with decision support systems and risk communication tools [14].

In the context of occupational risk management, decision-making becomes pivotal in achieving specific objectives related to addressing intellectual challenges by evaluating various criteria considering available information and possible solutions. Decision-making aims to overcome obstacles and complications in the process of choosing the best available option for the effective implementation of risk control measures, especially when there is ambiguity, uncertainty, and insufficient information [15]. Multi-criteria decision making (MCDM) approach, also known as multi-criteria decision analysis (MCDA), support decision making by considering the pros and cons of different options. The ranking or comparison is based on explicit criteria, which indicate aspects of the measures that should be considered during decision making process to reduce the uncertainties. Generally, experts' opinions are expressed verbally; therefore, evaluating a risk situation or decision making may require expert opinions about which there may be little or no detailed quantitative information [15, 16]. General Technique for Evaluating Control Measures (GTECM) examines and ranks control measures by integrating Haddon matrix and using Fuzzy Analytic Hierarchy Process (FAHP) to solve the ambiguity and complications caused by verbal judgment of experts. In this method, evaluating criteria are divided into 3 categories of Haddon matrix, risk factors and quality factors [15].

This study proposes a health risk management framework for workplaces which deal with manufactured nanomaterials, using a multi-criteria decision-making approach in line with control banding method to assess risks and evaluate control measures. Especially in Iran, the absence of structured risk management approaches, regulatory policies, interdepartmental coordination, and limited expertise poses significant challenges regarding human health in nanomaterials workplaces. To address these issues, we conducted available valid measures to bridge information gaps, reduce uncertainties, enhance employee health, and engage stakeholders for developing effective risk management.

2. Materials and methods

The health risk components within nanomaterials occupational settings were extracted through literature review and eventually in expert brainstorming sessions. The relevant literature from databases such as Web of Science, PubMed, and Scopus were assessed. Additionally, we gathered data from published documents provided by the US National Institute for Occupational Safety and Health (NIOSH), European Chemicals Agency (ECHA), European Commission (EU CORDIS), Organization for Economic Co-operation and Development (OECD), World Health Organization (WHO), International Organization for Standardization (ISO), Institute of Standards & Industrial Research of Iran (ISIRI).

The experts panel included comprised nanomaterial producers and pioneers, specialists in science and nanotechnology, and also occupational health and safety experts well-versed in workplace risk management. The 8 experts consisted of nanomaterial producers and pioneers, specialists in nanoscience and nanotechnology, and occupational health and safety experts with extensive experience in workplace risk management. The eight experts were selected according to predefined academic and professional criteria, including holding at least a master's degree, possessing relevant knowledge and practical experience in nanotechnology or occupational health risk management, and demonstrating both willingness and capacity to actively contribute to the study. This ensured that the panel integrated both technical expertise and applied perspectives.

The sessions were held with the aim of reaching a consensus to determine a risk assessment approach for the manufactured nanomaterials health risks based on a 3-layered semi-quantitative method. Analyzing the collected data and reaching consensus of experts panel were used in brainstorming sessions. The principles and rules governing the brainstorming sessions were considered by the supervisor [17]. All discussions and inputs from the expert meetings were systematically documented in written transcripts. These transcripts were then subjected to a structured qualitative content analysis. First, statements were coded into thematic categories such as hazard identification, exposure scenarios, and control measures. Second, frequency and convergence of

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opinions within each category were examined to identify areas of consensus versus disagreement. In cases where divergent views were observed, these were reintroduced into subsequent rounds of discussion until a stable consensus was achieved. This iterative analysis ensured that the final framework was not only based on individual expert opinions, but on systematically aggregated and validated knowledge across the panel.

Hazard banding (H-band)

For determination of the level of nanomaterials health hazards, hazard banding was carried out from H1 for the least and H5 for the most dangerous band. The 1st layer of hazard banding was based on the classification of the GHS using SDS data. In the 2nd layer, the NIOSH method for occupational exposure banding (OEB) and the classification of occupational exposure limits (OELs) was used. As for the 3rd layer, the classification was carried out based on physicochemical characteristics of manufactured nanomaterials, retrieved from NanoSafeIII tool [18].

GHS classification based on H-codes (SDS)

First layer of hazard banding using GHS classification provides a standardized framework for classifying chemicals hazards based on their intrinsic properties, such as toxicity and reactivity. This classification represents different endpoints such as acute toxicity (systemic or lethal), skin irritation, eye damage, respiratory or skin sensitization, specific target organ toxicity with a single exposure (STOT-SE) or repeated exposure (STOT-RE), reproductive toxicity, and carcinogenicity, as presented in Table A2.

NIOSH occupational exposure banding for OEL and toxicity data (OEB)

Occupational exposure banding is a risk-based approach that categorizes chemical hazard levels into bands (e.g., low, moderate, high) based on available toxicity data. Also, OELs if available, represent permissible occupational exposure levels which can be helpful in both quantitative and qualitative risk assessment methods. Using both OEB and OEL classification, we refined our 2nd layer for hazard banding to overcome the possibility of the absence of sufficient data considering manufactured nanomaterials toxicity, using GHS classification. NIOSH method use dose-response values from toxicological studies for classification of occupational exposure limits (OEL), and the classification of toxicological parameters, as presented in Table A3. Also, to extend the possibility of hazard banding in this layer, the carcinogenicity classification of the International Agency for Research on Cancer (IARC) and the US National Environmental Protection Agency (EPA) were introduced. At this stage, the required information and toxicological data could be extracted from public valid databases. The benchmark dose (BMD) possess a higher valid priority to use in classification for further assessment as it is not statistically limited to a specific group of experimental doses and is not highly sensitive to changes in sample size [19]. A list of reliable sources was presented in Table A4.

Physiochemical characteristics banding (NanoSafeIII)

NanoSafeIII tool provides an approach for the determination of occupational health risk levels associated with nanomaterials. Thus, we used the concept of hazard classification based on physiochemical properties as our 3rd layer of hazard banding. Buitrago et al. developed a tool to determine the hazard level of nanomaterials health risks based on physicochemical characteristics, including chemical composition, surface chemistry, shape, particle diameter, aspect ratio, solubility in water, or physical state [18]. This classification can lead to the assignment of the nanomaterial hazard level to one of 5 bands based on known/expected effects on human health regarding physiochemical properties.

Exposure banding (E-band)

Exposure Banding was carried out using the E1 band as for the least, and the E4 band as for the most probable scenario of being exposed to nanomaterials, specifically by inhalation, during manufacturing process. Also, another 3-layer approach based on the exposure probability in an occupational setting was introduced, taking into account the characteristics of the manufacturing process, the physical state, the amount of material used, the probability of the dust creation in the process, and the data obtained from actual exposure measurements, if possible.

For the 1st and 2nd layer, our banding was retrieved from the classification of ISO/TS 12901, and for the 3rd layer, the Paik et al. control banding method [20] was used. At this stage, the estimation of exposure potential for people who deal with nanomaterials was divided into 4 exposure bands from E1 (lowest exposure potential) to E4 category (highest exposure potential).

Process characteristics classification (ISO/TS 12901)

In the second layer of exposure banding, the classification of exposure was done by considering the manufacturing process of nanomaterials and the estimation of the probability of nanomaterials becoming airborne (e.g., solid, mist or gas) in the workplace environment. Our literature review based on ISO guidelines, lead to a list of nanomaterials manufacturing methods. The technical classification has been not the main goal. Then the probability of the exposure was considering different types of synthesis methods [21], which will be discussed later.

Physical state classification (ISO/TS 12901)

The second layer was based on the represented classification of ISO guideline considering the physical state of a given nanomaterial to estimate the level of exposure. This classification also considers the probability and estimation of nanomaterials becoming airborne during process, thus leading to the exposure for worker. Although it is recommended that in addition to the physical state, other properties such as brittleness, viscosity and volatility should also be considered [21, 22].

Working conditions classification (CB tool)

The third layer was retrieved from the control banding

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and scoring system of Paik et al. [20] CB tool as another possible way for exposure banding. This was done considering the workplace condition parameters, such as the probable number of exposed people, the amount of nanomaterials used during processes and the time required for performing the high-risk tasks.

Risk banding (R-band e.g., control banding)

The risk level of nanomaterials was divided into a range of 5 levels from R1 (lowest) to R5 (highest) determined based on the hazard and exposure bands integrating with risk level matrix described in the ISO/TS 12901. Using this guideline template, the risk banding was designed in the form of a decision tree. Decision tree systems are used in risk assessment methods when available data are insufficient or ordinal [22].

Evaluating control measures

A list of available and applicable control measures for the health risk management in nanomaterials workplaces was gathered through literature review, thus integrating them into the hierarchy of control measures for further evaluation [23]. For this purpose, we used General Technique for Evaluating Control Measures (GTECM) regarding Haddon Matrix, Risk Factors and Quality Factors. GTECM uses rating scales with linguistic variables to evaluate control measures to determine the importance of each. In the GTECM method, in addition to the Haddon matrix, other groups of decision-making criteria including risk and quality factors were also evaluated based on the consensus of the expert group's opinions and the corresponding score (See Fig. 2A) [15]. The Haddon Matrix (HM) is a conceptual framework used in risk management, particularly for analyzing, understanding and preventing events [24]. Matrix components evaluate that in which time stage (e.g., before, during, or after) of an event (e.g., exposure to nanomaterials), and on which element of a system (e.g., human, physical environment, social environment, and machine/equipment) every risk control measure applies to [25, 26]. According to GTECM, each cell has a local weight based on FAHP, which will be counted as 'HM' score for any control measure which will be used in further calculations (See Table A5).

Risk factors (RF score)

As a general concept, risk is characterized by the severity of a consequence and its likelihood of occurrence. However, sometimes risk factors extend beyond severity and probability. The Fine Kinney method computes risk based on probability, exposure frequency, and severity [27]. Similarly, some other methods obtain risk priority number using severity, probability, and detectability [28]. Risk is determined by multiplying relevant parameters to calculate risk scores and prioritize hazards for implementing appropriate control measures. According to GTECM, the weight of risk factors was presented as described in Table 1. Risk factors (RF) score was calculated using equation (1).

$$\text{Risk factor score RF} = (0.374 \times \mathrm{W_S}) + (0.211 \times \mathrm{W_P}) + (0.190 \times \mathrm{W_E}) + (0.225 \times \mathrm{W_D}) \tag{1}$$

Table 1. Weight of Risk factors according to GTECM [15].

Risk factor	Symbol	Weight
Risk severity	W_S	0.374
Risk probability	W_P	0.211
Exposure frequency	W_E	0.190
Detectability	W_D	0.225

Quality factors (QF score)

Quality factors play crucial roles in the implementation or selection of risk control measures through a risk management process. Such factors can be the cost of implementing a control or the duration required for it. Other factors such as reliability, usability in the system and risk reduction strategy (e.g., elimination, substitution, and etc.) can also be pivotal when selecting available control measures during a risk assessment process [15]. According to method, weight of quality factors is described in Table 2. Quality factors (QF) score was calculated using equation (2).

$$\text{Quality factor score QF} = (0.161 \times \mathrm{W_A}) + (0.199 \times \mathrm{W_R}) + (0.191 \times \mathrm{W_C}) + (0.169 \times \mathrm{W_{St}}) + (0.183 \times \mathrm{W_U}) + (0.097 \times \mathrm{W_{Du}}) \tag{2}$$

Table 2. Weight of Quality factors according to GTECM [15].

Risk factor	Symbol	Weight
Applicability	W_A	0.161
Reliability	W_R	0.199
Cost	W_C	0.191
Strategy	W_{St}	0.169
Usability	W_U	0.183
Duration	W_{Du}	0.097

Overall score (OS)

The evaluated factors were given a score (W_i) corresponding to the rating weight for every control measure. The panel of experts was asked to announce their score for each of the Haddon matrix, risk, and quality factors. According to GTECM, local weights for HM, RF, and QF scores were 0.153, 0.517, and 0.330, respectively. Therefore, the overall score (OS) for any given control measure was obtained using equation (3), and according

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to Table 3, thus decisions and judgments could be made regarding the evaluation of that control measure.

$$\text{Overall score OS} = [(0.153 \times \text{HM}) + (0.517 \times \text{RF}) + (0.330 \times \text{QF})] \times 100 \tag{3}$$

Table 3. Interpretation of ranking control measures according to GTECM [15].

Judgement or Ranking	Overall Score (OS)
Poor (P)	3.6 to 13.5
Fair (F)	13.6 to 23.4
Good (G)	23.5 to 33.2
Outstanding (O)	33.3 to 43.1

Rating factors (Wi scores)

According to GTECM and based on the absolute AHP method, we used a 5-scale rating consisting of excellent (O), good (G), average (A), poor (F) and very poor (P) to weight factor for any given control measure in nanomaterials occupational settings. Each rank in the spectrum was weighted 0.53, 0.24, 0.13, 0.06 and 0.04 respectively [15] according to the GTECM. After analyzing the above characteristics of all the control measures, a decision-support analysis for the effect of each control measure on the level of risk and other factors was done. We developed the scoring variables linguistic description for each risk and quality factors according to GTECM, as shown in Tables 4, and 5 respectively.

Reliability measurement

The concept of agreement between raters is used to evaluate the results of a method that is used by several people, in order to check inter-rater reliability. In the 1960s, Jacob Cohen introduced the inter-rater agreement method in order to measure inter-rater reliability [29, 30, 31]. Cohen's kappa coefficient 'κ' was used to measure the inter-reliability of the developed risk management framework. Raters in 9 random binary groups were asked to use the proposed method in the framework to assess the health risk in nanomaterials workplaces. In each group, the first rater learned the necessary training related to the concepts, development process and how to use the framework, specifically in the field of hazard and exposure banding, assessment and health risk management of nanomaterials, including how to acquire data, how to use the classification and how determine H, E, and R bands. The second rater (in a hypothetical random group) did not have the necessary expertise in the field of nanomaterials risk management and just determined the output of the banding level, respective to the given information for the nanomaterial (e.g., GHS classification code or toxicity dose-response value). They were given the required data, and only used the decision tree to obtain H, E, and R bands. The raters used the developed banding method in the work environment for the most used nanomaterials in Iran, and the agreement rate was calculated using Cohen's kappa coefficient according to the equation (4). The expression po is the observed relative agreement between raters, and pe is the percentage of the expected agreement. Kappa coefficient was evaluated based on the data represented in Table A6. Equation (4). Cohen's kappa coefficient [30]

$$\kappa = \frac{p_o - p_e}{1 - p_e} \tag{4}$$

3. Results and discussion

After the literature review data was extracted based on the opinions of the expert panel, the components affecting the health risks of nanomaterials were divided into 2 hazard and exposure groups, shown in Table 6.

Hazard banding based on GHS classification (layer 1)

The GHS classification system provides useful information regarding the potential hazards of chemicals in the form of Safety Data Sheets (SDS). Eastlake et al. evaluated the reliability of safety data sheets for 67 commercially available nanomaterials using a scoring system and showed that only 36% were not completely reliable [41]. The H-banding based on the classification of the GHS system is presented below in the Table 7.

Hazard banding based on NIOSH occupational exposure banding (layer 2)

NIOSH exposure/toxicity data classification was used in H-banding nanomaterials in a structured way to accurately determine the level of potential hazard to human health. The process of classification based on quantitative and qualitative information using dose-response or toxicity data from scientific research results is defined in 5-scale categories A to E, which was used respectively as H-bands [19].

The lower the concentration or dose of toxic effects, the more severe the potential toxicity of that substance is and the higher the H-band. The hazard spectrum along with the classification of exposure limits, if available, is used to determine the hazard level of nanomaterials and to make decisions regarding control measures in work environments, as in Tables 8 and 9.

If no relevant data are available for occupational exposure limits for hazard banding of nanomaterials, the worst case (band H5) should be considered for that material. In relation to the classification of toxicological dose-response values, the NIOSH method recommends to use the benchmark dose level (BMDL) as risk classification criterion. NOAEL and LOAEL values can also be used in hazard banding.

According to the objectives of the study and maintaining a uniform approach in the working method, the second part of the classification of health risks of nanomaterials as H1 (as the lowest risk) to H5 (as the highest

Table 4. Scoring variables linguistic description for risk factors using GTECM method [15].

Variable (score)	Linguistic description
	Severity (W_S)
Outstanding (0.53)	A risk control measure that reduces the hazard severity to H1, or the consequence of MNM exposure to the following: first aid, no loss of working time, very minor financial and environmental effects.
Good (0.24)	A risk control measure that reduces the hazard severity to H2, or the consequence of MNM exposure to the following: medical service, few days of lost work, minor financial damage and reversible environmental effects.
Average (0.13)	A risk control measure that reduces the hazard severity to H3, or the consequence of MNM exposure to the following: partial disability or hospitalization, significant financial damage and reversible environmental effects.
Fair (0.06)	A risk control measure that reduces the hazard severity to H4, or the consequence of MNM exposure to the following: Injury or disease with total disability, large financial loss, and significant environmental effects.
Poor (0.04)	A risk control measure that has no noticeable effect on mitigation of risk severity, and death, huge financial loss, irreversible and catastrophic environmental effects may still happen.
	Probability (W_P)
Outstanding (0.53)	A risk control measure that reduces the exposure probability to E1, or have impact on the following: huge reduction in amount of nanomaterial used, working time, and number of people exposed to the nanomaterial.
Good (0.24)	A risk control measure that reduces the exposure probability to E2, or have impact on the following: large reduction in amount of nanomaterial used, working time, and number of people exposed to the nanomaterial.
Average (0.13)	A risk control measure that reduces the exposure probability to E3, or have impact on the following: significant reduction in amount of nanomaterial used, working time, and number of people exposed to the nanomaterial.
Fair (0.06)	A risk control measure that reduces the exposure probability to E4, or have impact on the following: minor reduction in amount of nanomaterial used, working time, and number of people exposed to the nanomaterial.
Poor (0.04)	A risk control measure that increases the exposure probability, or have negative impact on the following: increased amount of nanomaterial used, working time, and number of people exposed to the nanomaterial.
	Frequency (W_E)
Outstanding (0.53)	A control measure that after its implementation, there is no possibility of repeated exposure in the life cycle of nanomaterial.
Good (0.24)	A control measure that after its implementation, the possibility of repeated exposure is unlikely, but is expected to occur during the life cycle of the given nanomaterial.
Average (0.13)	A control measure that after its implementation, the possibility of repeated exposure is likely, and may repeat exposure in the life cycle of the given nanomaterial.
Fair (0.06)	A control measure that after its implementation, is expected to repeat the exposure in the life cycle of the given nanomaterial.
Poor (0.04)	A control measure that does not have a noticeable effect on reducing the repetition of exposure in the life cycle of the nanomaterial, and may pose a negative effect.
	Detectability (W_D)
Outstanding (0.53)	A control measure that provides an outstanding and very high level of risk detection. This can be achieved both by hazard and exposure detection.
Good (0.24)	A control measure that provides a high level of risk detection. This can be achieved both by hazard and exposure detection.
Average (0.13)	A control measure that provides a moderate level of risk detection. This can be achieved both by hazard and exposure detection.
Fair (0.06)	A control measure that provides a low level of risk detection. This can be achieved both by hazard and exposure detection.
Poor (0.04)	A control measure that provides no risk detectability, and may even have a negative effect.

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Table 5. Scoring variables linguistic description for quality factors using GTECM method [15].

Variable (score)	Linguistic description
	Applicability (W_A)
Outstanding (0.53)	It is completely possible to implement the control measure on existing technical and management systems and adapt them to equipment, working conditions, technology and operational procedures.
Good (0.24)	It is possible to implement the control measure on existing technical and management systems and adapt them to equipment, working conditions, technology and operational procedures.
Average (0.13)	It is almost possible to implement the control measure on existing technical and management systems and adapt them to equipment, working conditions, technology and operational procedures.
Fair (0.06)	It is not possible to implement the control measure on existing technical and management systems and adapt them to equipment, working conditions, technology and operational procedures.
Poor (0.04)	It is completely impossible to implement the control measure on existing technical and management systems and adapt them to equipment, working conditions, technology and operational procedures.
	Reliability (W_R)
Outstanding (0.53)	Correct operation probability of the control measure in predefined conditions, is very high.
Good (0.24)	Correct operation probability of the control measure in predefined conditions, is high.
Average (0.13)	Correct operation probability of the control measure in predefined conditions, is moderate.
Fair (0.06)	Correct operation probability of the control measure in predefined conditions, is low.
Poor (0.04)	Correct operation probability of the control measure in predefined conditions, is very low.
	Cost (W_C)
Outstanding (0.53)	Financial budget required to implement the control measure is completely affordable and acceptable.
Good (0.24)	Financial budget required to implement the control measure is affordable and acceptable.
Average (0.13)	Financial budget required to implement the control measure is almost affordable and acceptable.
Fair (0.06)	Financial budget required to implement the control measure is not affordable and acceptable.
Poor (0.04)	Financial budget required to implement the control measure is completely unacceptable.
	Strategy (W_{St})
Outstanding (0.53)	The control measure is categorized as ‘elimination’ within the hierarchy of control measures.
Good (0.24)	The control measure is categorized as ‘substitution’ within the hierarchy of control measures.
Average (0.13)	The control measure is categorized as ‘engineering’ within the hierarchy of control measures.
Fair (0.06)	The control measure is categorized as ‘administrative’ within the hierarchy of control measures.
Poor (0.04)	The control measure is categorized as ‘personal protective’ within the hierarchy of control measures.
	Usability (W_U)
Outstanding (0.53)	Implementation of the control measure is completely acceptable for providing user satisfaction.
Good (0.24)	Implementation of the control measure is acceptable for providing user satisfaction.
Average (0.13)	Implementation of the control measure is almost acceptable for providing user satisfaction.
Fair (0.06)	Implementation of the control measure is not acceptable for providing user satisfaction.
Poor (0.04)	Implementation of the control measure is completely unacceptable for providing user satisfaction.
	Duration (W_{Du})
Outstanding (0.53)	The time required to implement the control measure is completely affordable and acceptable.
Good (0.24)	The time required to implement the control measure is affordable and acceptable.
Average (0.13)	The time required to implement the control measure is almost affordable and acceptable.
Fair (0.06)	The time required to implement the control measure is not affordable and acceptable.
Poor (0.04)	The time required to implement the control measure is completely unacceptable.

Table 6. Components affecting the health risks of manufactured nanomaterials in the workplace.

Component	Band group	Description	Reference
Particle size	Hazard	The smaller the diameter (below 100 nm), the greater the potential toxicity due to increased specific surface area [32].	Gatoo, et al.
Particle shape	Hazard	For fibers or rods, inflammatory response will be greater due to high penetration ability through biological barriers [32].	Gatoo, et al.
Aspect ratio	Hazard	The higher the aspect ratio, the more the nanoparticle will be in the form of fibers, increasing the absorption rate [33].	Fubini, et al.
Surface chemistry	Hazard	The surface characteristics lead to oxidative stress, metabolic disorders and genetic damage [33].	Fubini, et al.
Solubility	Hazard	Insoluble nanoparticles remain in the body for a long time. Accumulation in body tissues causes production of reactive substances and oxidative stress. Insoluble nanofibers may remain in the lungs for a very long time [32].	Gatoo, et al.
Chemical composition	Hazard	The release of metal ions, reactive oxygen species can affect toxicity and lead to fibrosis or target organ failure [32].	Gatoo, et al.
Aggregation	Hazard	The process of clearing accumulated nanomaterials from the body, becomes more difficult [34].	Murugadoss, et al.
Bonding energy	Hazard	Affects the potential of cell damage by affecting reactivity and production of reactive oxygen species [18].	Buitrago, et al.
Morphology	Hazard	Some nanoparticles may cause long-term inflammatory responses due to their needle-like shape [21].	Baig, et al.
Manufacturing process	Exposure	The manufacturing process affects the risk of nanomaterials by using different physical states. Mechanical treatment on nanomaterials increases the probability of exposure [35].	Abbott, et al.
Physical state	Exposure	For powdered nanomaterials, the probability of inhalation and respiratory exposure is higher due to aerosol creation [35].	Abbott, et al.
Duty time	Exposure	By increasing the time of working with nanomaterials, the probability of exposure will be higher [36].	Woskie, et al.
Task frequency	Exposure	With increasing frequency of exposure to nanomaterials, the probability of exposure will be higher [37].	Zalk, et al.
Amount of material	Exposure	By increasing the amount of nanomaterial used, the probability of exposure will be higher [37].	Zalk, et al.
Number of people exposed	Exposure	If more people are exposed to nanomaterials, the accumulated risk will be higher [38].	Marquart, et al.
Air profile	Exposure	Exposure modeling results could be effective in nanomaterials risk management, [39].	Marquart, et al.

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Table 7. GHS classification for chemical hazards [40].

Toxicity	GHS Classification	H-code in GHS	Hazard description	H-band
Acute Lethal Toxicity	1, 2	H300, H310, H330	Fatal if swallowed, inhalation or skin contact	H4
	3	H301, H311, H331	Toxic if swallowed, inhalation or skin contact	H3
	4	H302, H312, H332	Harmful if swallowed, inhalation or skin contact	H2
	5	H303, H313, H333	Maybe harmful if swallowed, inhaled or contact	H1
Acute systemic Toxicity	1	—	Acute systemic toxicity	H3
	2	—	Acute systemic toxicity	H2
Sensitization	1, 1A	H317	Allergic skin reaction	H4
	1B	H317	Allergic skin reaction	H3
Skin corrosion, irritation	1	H314	Severe skin burns	H5
	2	H315	Skin irritation	H3
	3	H316	Mild skin irritation	H2
Eye damage	1	H318	Serious eye damage	H4
	2, 2A	H319	Serious eye irritation	H3
	2B	H320	Eye irritation	H2
Aspiration hazard	1	H334	Respiratory sensitization, allergy, asthma	H5
	1	H304	Fatal if inhaled, swallowed	H5
	2	H305	Harmful if inhaled, swallowed	H3
Germ cell mutation	1, 1A, 1B	H340	Cause genetic defects	H5
	2	H341	Suspected of causing genetic defects	H3
Carcinogenicity	1, 1A, 1B	H350	May cause cancer	H5
	2	H351	Suspected of causing cancer	H5
Toxic to reproduction	1, 1A, 1B	H360	May damage fertility or unborn child	H5
	2	H361	Suspected of damage to fertility or unborn child	H4
	—	H362	May harm breast-fed child	H3
Target organ (STOT-SE)	1	H370	Cause damage to organ	H5
	2	H371	May cause damage to organ	H4
	3	H335, H336	May cause respiratory irritation	H3
Target organ (SOT-RE)	1	H372	Cause damage to organ	H4
	2	H373	May cause damage to organ	H3

Table 8. NIOSH classification for occupational exposure limits [19, 20].

Nanomaterial state	Measurement unit of OEL	Classification of OEL (H-band)				
		H1	H2	H3	H4	H5
Nanoparticle	µg/m^3 (8hr)	> 10	1 to 10	0.1 to 1	0.01 to 0.1	< 0.01
Vapor/Gas	ppm	> 10	1 to 10	0.1 to 1	0.01 to 0.1	< 0.01
Bulk material	µg/m^3 (8hr)	> 1000	100 to 1000	10 to 100	1 to 10	< 1

Table 9. NIOSH occupational exposure banding (OEB) [19, 20].

Toxicity parameter	Route	Index	Unit	Classification of dose-response data (H-Band)				
				H1	H2	H3	H4	H5
Acute toxicity	Ingestion	LD50	mg/kg-bw	> 2000	300 to 2000	50 to 300	5 to 50	< 5
	Skin contact	LD50	mg/kg-bw	> 2000	1000 to 2000	200 to 1000	50 to 200	< 50
	Inhalation	LC50	mg/L-4hr	> 5	1 to 5	0.5 to 1	0.05 to 0.5	< 0.05
Reproductive toxicity	Ingestion	BMDL	mg/kg-bw	> 300	30 to 300	3 to 30	0.3 to 3	< 0.3
	Skin contact	BMDL	mg/kg-bw	> 300	30 to 300	3 to 30	0.3 to 3	< 0.3
STOT-RE	Ingestion	BMDL	mg/kg-bw	> 1000	100 to 1000	10 to 100	1 to 10	< 1
	Skin contact	BMDL	mg/kg-bw	> 1000	100 to 1000	10 to 100	1 to 10	< 1
	Inhalation	BMDL	mg/kg-bw	> 30	3 to 30	0.3 to 3	0.03 to 0.3	< 0.03
Carcinogenicity	Injection	TD05	mg/kg-bw	-	-	> 5	0.005 to 5	< 0.005
	Inhalation	TC05	mg/m^3	-	-	> 16.7	0.005 to 16.7	< 0.005

risk) is equivalent to the classification A to E of the NIOSH method based on toxicity doses, as described in Table 9.

Hazard banding based on physiochemical properties (layer 3)

Buitrago et al. developed a decision tree based on the physicochemical characteristics of nanomaterials for hazard banding, including surface chemistry, shape, particle diameter, aspect ratio, solubility in water, chemical composition or physical state [18], as shown in Table 10.

In the present study, the health risk level of manufactured nanomaterials is determined by integrating the band levels with the decision-tree pattern in the ISO 13849 standard. This pattern works as a graphic tool which may is used for selecting the minimum level of performance required for safety measures, when risk assessment data are limited or qualitative. It uses parameters such as risk severity, frequency or duration of exposure, the possibility of preventing and limiting damage as input to determine the performance level based on a decision-tree approach [42].

We aimed to represent the above classifications into the decision tree for hazard and exposure banding for better user experience. This could also lead to a tree-shape algorithm which could be used for developing a manual in future. Hazard bands classification for 3 above layers are represented in figures A3-6.

Exposure banding based on process characteristics (layer 1)

According to Baig et al. [21], two main approaches are used for manufacturing nanomaterials (e.g., top-down methods, and bottom-up methods). In top-down methods, raw materials are used to produce nanoparticles which include mechanical milling, laser ablation, and etc. First layer of exposure banding was done according to the classification of ISO/TS 12901 standard guidance

Table 10. Hazard banding interpreted from NanoSafeIII [18].

Nanomaterial	Classification criteria	Effective component	H-band
Stable nanofibers	Nanomaterial group	Shape, aspect ratio, biological resistance	H5
Unstable nanofibers	Nanomaterial group	Shape, aspect ratio, biological resistance	H3
Fullerene	Carbon nanomaterials	Chemical mixture	H3
Carbon black	Carbon nanomaterials	Chemical mixture	H3
Graphene	Carbon nanomaterials	Chemical mixture	H3
Nano diamond	Carbon nanomaterials	Chemical mixture	H1
Nanomaterials with stable coating	Mineral coating	Surface coating	On core
Nanomaterials with unstable coating	Mineral coating	Surface coating, biocompatibility	H1
Gold nanoparticles	Metallic nanomaterials	Particle size, chemical composition	On size
Platinum, Palladium, Iridium, Radium	Metallic nanomaterials	Particle size, chemical composition	H3

and data extracted through literature review. Ultimately, after integrating into decision-tree pattern, is shown in figure 1.

Exposure banding based on material physical state (layer 2)

For the second layer of exposure banding, ISO/TS 12901 lead to a decision tree based on the physical state of the nanomaterials used. According to the control banding approach, exposure banding based on the physical characteristics for nanomaterials in solid matrix, nanomaterials suspended in a liquid (Emulsion), and powdered nanomaterials are shown in figures 2-4, respectively.

Exposure banding based on working conditions (layer 3)

In this layer, exposure banding was based on Paik et al. model [20], regarding the number of people exposed to nanomaterials, the amount of nanomaterials used in the process, and the time of performing high-risk tasks. There is a positive correlation between the amount or weight of nanomaterials used in a single-run process, and the number of people exposed, the frequency of task repeats and the time of performing the risky task with the level of health risk. Former method used scoring system for above factors, which was transformed into decision tree after integration with ISO 13849 pattern, as presented in figure 5.

Risk level decision tree (R-band)

In final part, the decision tree of risk band was presented in a 5-scale spectrum as R1 for the lowest risk to R5 for the highest risk after integration of hazard and exposure bands, as shown in figure 6. H and E represent the level of hazard and exposure bands in the decision tree for risk assessment algorithm, respectively.

Hierarchy of control measures

Data extracted from literature review of published guidelines for safe work with nanomaterials, lead to establish a list of 38 control measures for nanotechnology occupational settings (See Fig. A7). These measures cover a wide range of risk mitigation methods and applications which should be used respectively, to the identified risk level and quality factors [21, 22, 42, 43].

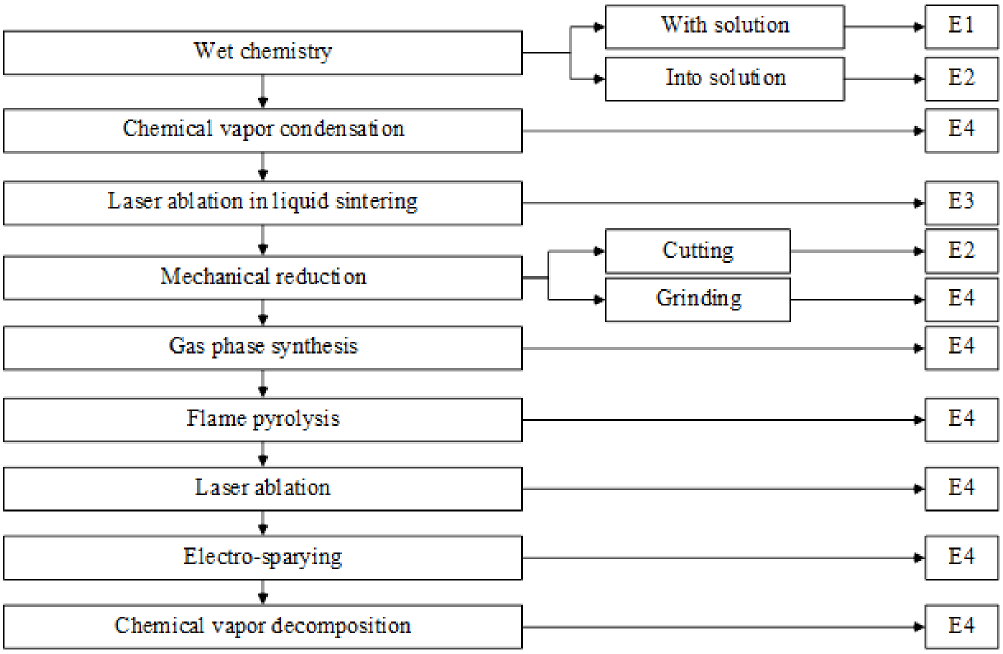

Figure 1. Decision tree for E-bands, based on process characteristics [21, 22].

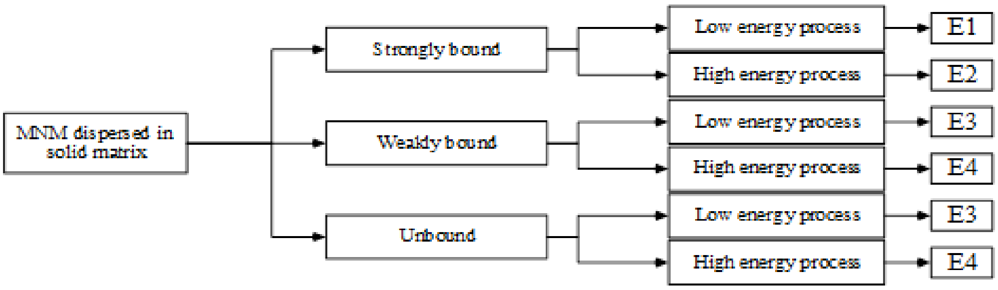

Figure 2. Decision tree for E-bands, based on material physical state for nanomaterials in solid matrix [21, 22].

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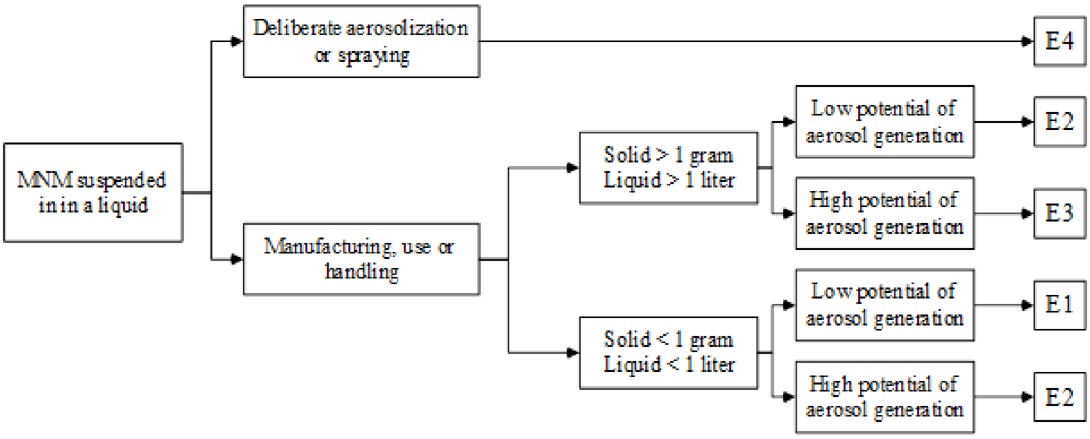

Figure 3. Decision tree for E-bands, based on material physical state for nanomaterials suspended in liquid [21, 22].

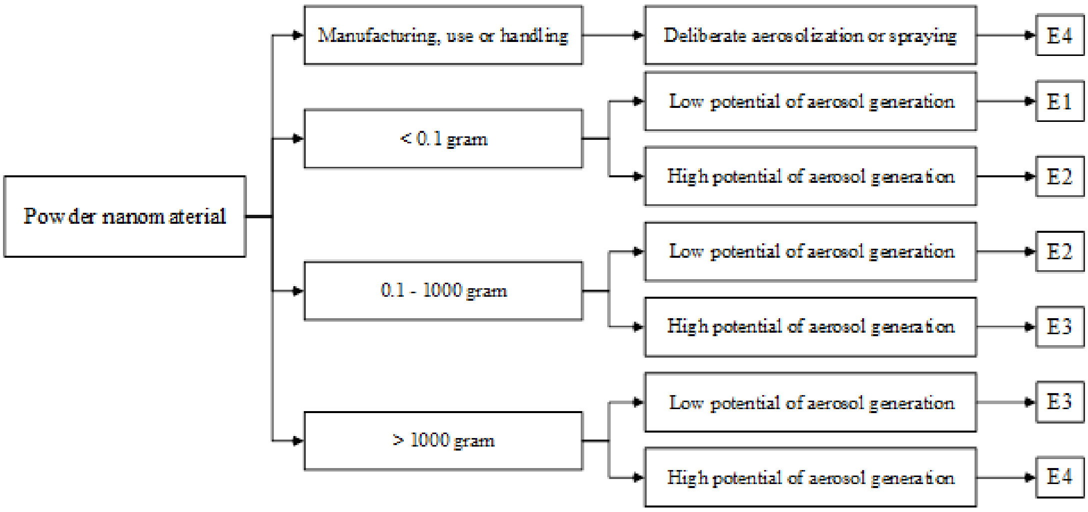

Figure 4. Decision tree for E-bands, based on material physical state for powder nanomaterials [21, 22].

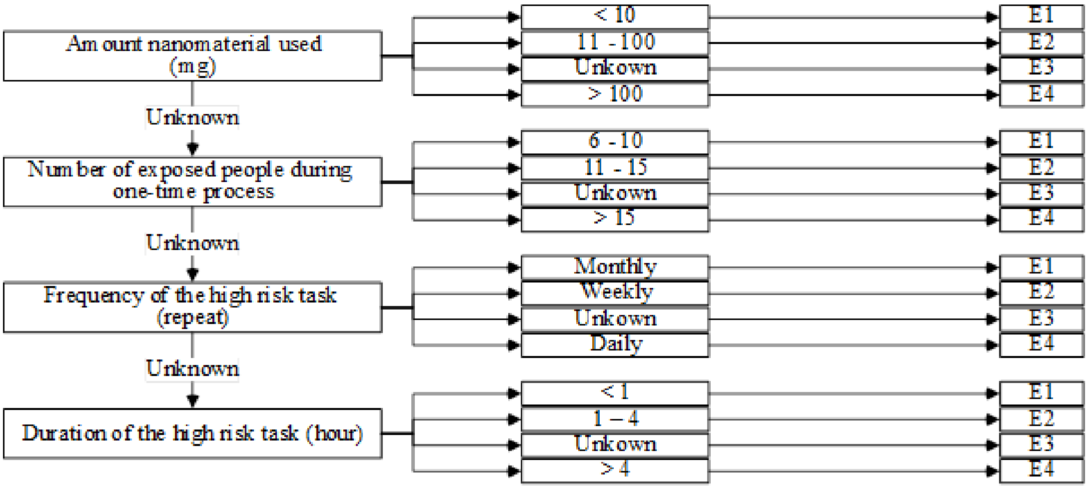

Figure 5. Decision tree for E-bands, based on material physical state for powdered nanomaterials [20].

Evaluation of control measures based on GTECM

After preparing the list of 38 control measures, ‘HM’ value was extracted according to the time stage and the effective element of each control measure. In the following, after the consensus of the opinions of the expert panel, risk and quality factors scores were also calculated for the control measures and finally lead the

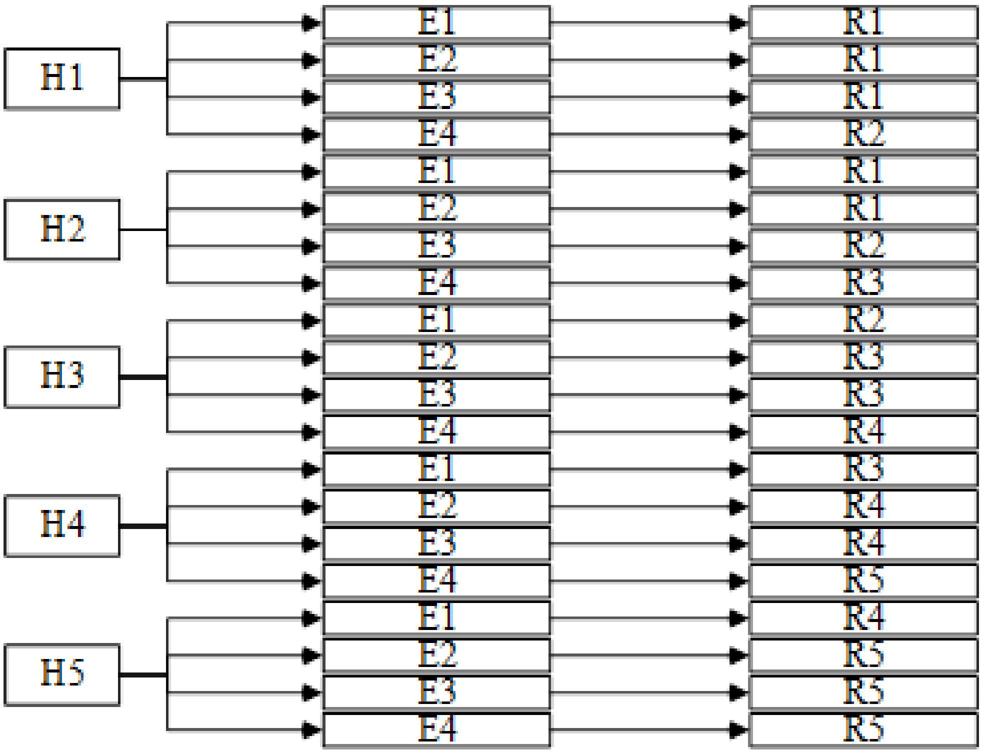

Figure 6. Decision tree for risk level, R-band [21, 22, 42, 43].

overall score for each of 38 control measures (OS). Next, analysis was done based on risk factor and quality factors for every control measure to give a better interpretation for risk managers when selecting and implementing control measure in nanomaterials occupational settings, as shown in Table 11.

It is recommended that the measures which have been rated 'excellent', 'good', and 'average', respectively, should be prioritized. Considering that in this method, the general basis of judgment is based on the overall score, any measure with a higher rating is given priority. It should be noted that the ranking in this study is done in a general way and every organization can adjust according to the existing policies, conditions and overall risk level. According to the relationship between risk level and the hierarchy of control measures, after interpreting and reviewing the guidelines of the WHO and NIOSH in order to reduce the risk and protect workers engaged in working environments with nanomaterials, the proposed control measures are proposed in Table 11. However, it should be noted that the exact effectiveness of each control measure should be examined in future studies.

Through the analysis of the control measures' ratings, their characteristics were interpreted in terms of risk and quality factors, in order to provide a guidance and decision support system for manager and decision-making process in risk management. Regarding the medium risk level, pay attention to protection through personal protective equipment. For high and very high-risk levels, the implementation of extensive technical measures becomes necessary. Administrative measures, such as training sessions, technical sessions or establishing a permit-to-work system for working with nanomaterials, should be implemented.

Results of characterizing the direct effectiveness of any control measure more precisely, by identifying a path from the risk decision tree are presented in Table 12. These results suggest that by implementing a control measure, how the risk will be directly reduced.

In order to use the developed method and examine results, the method was used in Iranian nanotechnology companies and laboratories (Nanomaterial's laboratory of oil industry research institute, and other companies in the field of nanomaterials) working with manufacturing, production and exploitation of nanomaterials, and its results are presented in the Table 13. Thus, at this stage, after the identification of commonly used nanomaterials in Iran, physicochemical characteristics were determined and toxicological data were collected from databases, and the results were presented as followed.

If a specific classification of nanomaterial hazards in question is not available based on the GHS system, or the toxicity doses have not been determined in recent studies, it should not be concluded that there is no risk. In such a situation, the principle of caution should be observed in deciding to select and implement control measures or use other layers in this method which could lead into risk level and control measure selection.

Inter-rater reliability analysis

The developed method was used by 19 people in random binary trained and untrained groups to assess the

Table 11. Evaluating control measure based on GTECM (decision-support matrix 1).

Control measure in nanomaterials workplace	Haddon matrix	Overall score	Overall rate	Main risk factor	Main quality factor	Suggested R-band
Eliminate material, work task or process	Pr-M	31.5	Good	Severity (O*)	Cost, Applic.[1] (P*)	R4 - R5
Substitute material, hazardous process, or task	Pr-M	31.5	Good	Severity (O)	Cost, Applic. (P)	R3 - R5
Reduce amount of material, or size of containers	Pr-M	18.5	Fair	Probability (G*)	Cost, Usability (F*)	R3 - R5
Physical change and solubility of matter	Pr-M	21.2	Fair	Severity (G)	Cost, Usability (F)	R3 - R5
Change material physicochemical characteristics	Pr-M	17.0	Fair	Severity (F)	Cost, Usability (F)	R3 - R5
Implement fully automatic process	Pr-M	33.2	Good	Prob.[2] Frequ.[3] (O)	Cost, Applic. (P)	R4 - R5
Install water spray over the source locally	Ev-P	15.6	Fair	Prob. Frequ. (O)	Cost, Applic. (G)	R3 - R5
Use close system to transfer nanomaterials	Ev-M	19.4	Fair	Prob. Frequ. (G)	Cost, Applic. (P)	R3 - R5
Physical containment of contamination source	Ev-P	20.4	Fair	Prob. Frequ. (G)	Cost, Applic. (P)	R3 - R5
Physical confinement of the worker	Ev-H	17.0	Fair	Prob. Frequ. (G)	Usability (P)	R3 - R5
Install hood at the source of pollution	Ev-P	15.2	Fair	Prob. Frequ. (G)	Applicability (G)	R3 - R5
Negative pressure between room and corridor	Ev-P	11.4	Poor	Probability (F)	Applicability (P)	R4 - R5
Mechanical or natural ventilation	Ev-P	9.10	Poor	Prob. Frequ. (P)	Reliability (P)	R3 - R5
Use Clean-Room system	Ev-P	19.1	Fair	Prob. Frequ. (G)	Cost, Applic. (P)	R4 - R5
Use ceramic or resin on the floor of the workplace	Ev-P	12.7	Poor	Prob. Frequ. (G)	Cost, Applic. (F)	R4 - R5
Repair and maintenance of equipment and devices	Ev-M	16.2	Fair	Prob. Frequ. (G)	Cost, Applic. (G)	R1 - R5
Monitoring of air or ventilation parameters	Ev-M	12.2	Poor	Detection (P)	Strategy (F)	R3 - R5
Monitoring concentration of nanomaterials in air	Ev-P	13.6	Fair	Detection (P)	Strategy (F)	R3 - R5
Register nanomaterial statistics and information	Pr-S	18.8	Fair	Sev.[4] Prob. (G)	Applicability (O)	R1 - R5
Housekeeping of the workplace	Ev-H	17.9	Fair	Prob. Frequ. (G)	Applicability (O)	R1 - R5
Management of safety, health and environment	Ev-S	18.1	Fair	Prob. Frequ. (G)	Applicability (O)	R1 - R5
Access to nanomaterials safety data sheet	Ev-S	24.5	Good	Prob. Frequ. (G)	Applicability (O)	R1 - R5
Comply with principles of personal hygiene	Ev-H	15.1	Fair	Prob. Frequ. (F)	Reliability (F)	R1 - R5
Determine specific storage location	Ev-P	16.1	Fair	Prob. Frequ. (F)	Strategy (P)	R3 - R5
Packaging and labelling of nanomaterials	Ev-M	16.5	Fair	Prob. Frequ. (F)	Cost, Applic. (G)	R3 - R5
Establish permit-to-work system	Pr-S	18.4	Fair	Prob. Frequ. (F)	Cost, Applic. (G)	R3 - R5
Periodic risk management meetings	Pr-S	14.7	Fair	Sev. Prob. (G)	Cost, Applic. (O)	R1 - R5
Training for life cycle of nanomaterials	Pr-S	18.3	Fair	Sev. Prob. (G)	Cost, Applic. (O)	R1 - R5
Marking and labeling of nanomaterials	Pr-M	23.7	Good	Sev. Prob. (G)	Cost, Applic. (O)	R1 - R5
Nanomaterial spill cleaning in more efficient way	Po-M	18.4	Fair	Prob. Frequ. (G)	Cost, Applic. (O)	R3 - R5
Tend to employees' nutritional interventions	Pr-H	14.2	Fair	Detection (F)	Strategy (P)	R3 - R5
Monitoring the entry and exit or restricting access	Ev-S	14.3	Fair	Frequency (G)	Strategy (P)	R4 - R5
Reduce work duty time	Ev-H	22.8	Fair	Prob. Frequ. (G)	Strategy (P)	R3 - R5
Install signs and instructions for safe work	Pr-S	23.9	Good	Prob. Frequ. (G)	Cost, Applic. (G)	R1 - R5
Use protective clothing	Po-H	16.8	Fair	Applicability (F)	Usability (F)	R4 - R5
Use eye protection with safety glasses	Po-H	16.8	Fair	Applicability (F)	Usability (F)	R3 - R5
Use protective gloves	Po-H	16.8	Fair	Applicability (F)	Usability (F)	R3 - R5
Use respiratory protective equipment	Po-H	18.6	Fair	Applicability (F)	Usability (F)	R4 - R5

Abbreviations:
Pr: Pre-event Po: Post-event Ev: During-event
P: Physical environment S: Social environment H: Human M: Machine/Equipment
*O: Outstanding *G: Good *F: Fair *P: Poor
*1: Applicability *2: Probability *3: Frequency *4: Severity

Table 12. Direct effect of control measures on risk factors (decision-support matrix 2).

Control measure in nanomaterials workplace	Control strategy	Direct effect of control measure
Eliminate material, work task or process	Elimination	Changing intrinsic toxicity
Substitute material, hazardous process, or task	Substitution	Changing operating process, or powder form
Reduce amount of material, or size of containers	Substitution	Reducing amounts used, or time of use
Physical change and solubility of matter	Substitution	Changing operating process
Change material physicochemical characteristics	Substitution	Changing intrinsic characteristics, or potential toxicity
Implement fully automatic process	Engineering	Changing operating process
Install water spray over the source locally	Engineering	Changing powder form, or reducing aerosol creation
Use close system to transfer nanomaterials	Engineering	Changing powder form, or reducing aerosol creation
Physical containment of contamination source	Engineering	Changing powder form, or reducing aerosol creation
Physical confinement of the worker	Engineering	Protecting exposed people
Install hood at the source of pollution	Engineering	Changing powder form, or reducing aerosol creation
Negative pressure between room and corridor	Engineering	Changing powder form, or reducing aerosol creation
Mechanical or natural ventilation	Engineering	Changing powder form, or reducing aerosol creation
Use Clean-Room system	Engineering	Changing powder form, or reducing aerosol creation
Use ceramic or resin on the floor of the workplace	Engineering	Reducing aerosol creation
Repair and maintenance of equipment and devices	Engineering	Changing operating process, or reducing aerosol creation
Monitoring of air or ventilation parameters	Administrative	Reducing aerosol creation, protecting exposed persons
Monitoring concentration of nanomaterials in air	Administrative	Reducing aerosol creation, protecting exposed persons
Register nanomaterial statistics and information	Administrative	Educating toxicity hazards, or control amounts used
Housekeeping of the workplace	Administrative	Changing operating process, or reducing aerosol creation
Management of safety, health and environment	Administrative	Reducing aerosol creation, or protecting exposed people
Access to nanomaterials safety data sheet	Administrative	Changing intrinsic toxicity, or operating process
Comply with principles of personal hygiene	Administrative	Reducing aerosol creation
Determine specific storage location	Administrative	Reducing aerosol creation
Packaging and labelling of nanomaterials	Administrative	Changing powder form, or reducing aerosol creation
Establish permit-to-work system	Administrative	Reducing aerosol creation, or protecting exposed people
Periodic risk management meetings	Administrative	Reducing aerosol creation, or protecting exposed people
Training for life cycle of nanomaterials	Administrative	Changing intrinsic toxicity, operating process, or aerosol creation
Marking and labeling of nanomaterials	Administrative	Changing intrinsic toxicity, operating process, or aerosol creation
Nanomaterial spill cleaning in more efficient way	Administrative	Changing powder form, or reducing aerosol creation
Tend to employees' nutritional interventions	Administrative	Protecting exposed people
Monitoring the entry and exit or restricting access	Administrative	Protecting exposed people, reducing amounts used, or time
Reduce work duty time	Administrative	Protecting exposed people, reducing amounts used, or time
Install signs and instructions for safe work	Administrative	Changing intrinsic toxicity or operating process, Protecting people
Use protective clothing	PPE[1]	Protecting exposed people
Use eye protection with safety glasses	PPE	Protecting exposed people
Use protective gloves	PPE	Protecting exposed people
Use respiratory protective equipment	PPE	Protecting exposed people

*** Abbreviations:
*1: Personal protective equipment

health risk of selected nanomaterials separately. Rate of agreement between raters was calculated with Cohen's kappa coefficient, as a reliability index for the developed method, as presented in Table A7. For reliability analysis of the developed method, the values of 'po' as the percentage of observed agreement between rater and 'pe' as the percentage of expected agreement were calculated with the help of Excel, and in the final of Cohen's kappa coefficient was calculated 0.72. The agreement between the raters in the successful manner to determined hazard and exposure bands, lead to estimation of 'significant agreement' regarding Table 8.

4. Conclusion

The initial phase of this study involved a literature review to examine the methods, applicability, strengths, and limitations associated with developed risk management frameworks and tools for nanomaterials. While nanomaterials risk management frameworks possess inherent strengths and weaknesses, none can be deemed the most comprehensive or optimal. These frameworks and tools have adopted diverse approaches, methodologies, and criteria to address the complexities and hazards posed by nanomaterials, as well as insufficient data and stan-

Table 13. Risk assessment results for selected workplaces and nanomaterials.

Nanomaterial	Synthesis method	H-band	E-band	R-Band
Single-walled carbon nanofibers	Chemical vapor deposition, Electrospinning	H3	E4	R4
Amorphous silica nanoparticle	Wet chemistry (Sol Gel)	H1	E1	R1
Graphene	Chemical vapor deposition	H2	E4	R3
Zinc-oxide nanoparticles	Wet chemistry (Sol Gel)	H5	E1	R4
Titanium-dioxide nanoparticle	Wet chemistry (Sol Gel)	H1	E1	R1
Multi-walled carbon nanofibers	Chemical vapor deposition, Electrospinning	H4	E4	R5
Silver nanoparticles	Laser ablation, Chemical vapor condensation	H4	E4	R5
Carbon black	Mechanical milling	H4	E3	R4
Fullerene	Laser ablation	H3	E4	R4
Graphene-oxide	Spark deposition	H3	E4	R4
Bentonite nanowires	Suspended in liquid	H3	E2	R3
Carbon black	Suspended in liquid, Grinding	H4	E2	R4

dardization. Each framework or tool has distinct goals and perspectives, reflecting the diverse needs of experts in the field of nanotechnology risk management. Understanding these frameworks is crucial in the initial step to extend the collaboration and communication among stakeholders, and the sharing of knowledge regarding the potential hazards of these substances.

As of now, there are a limited resources, data, and expertise in the field of nanomaterials risk management. Therefore, with the aim of developing an assessment and decision-support framework with the perspective of a national (Iranian) tool for managing the health risks of nanomaterials in occupational settings, this study aimed to identify and review international frameworks and tools in order to achieve the main goals and vision.

Compared to international frameworks such as Stoffenmanager Nano and CB Nanotool, our proposed framework incorporates the General Technique for Evaluating Control Measures (GTECM) to provide a more integrated and practical approach to health risk assessment of manufactured nanomaterials in workplaces. While Stoffenmanager Nano primarily focuses on modeling airborne exposure to nanomaterials, its application can be limited in contexts where detailed exposure measurements or toxicological data are not available. In contrast, our framework combines hazard banding, exposure banding, and evaluation of control measures, allowing a semi-quantitative to qualitative assessment that can be applied even when empirical exposure data are scarce. This integration of control measure evaluation and multi-criteria decision-making distinguishes our method, providing a more adaptable tool for occupational health management, particularly in settings with limited monitoring resources.

Considering the high potential of innovation and economic extension in the field of nanotechnology in Iran, the establishment of an integrated and structured regulatory framework consisting of newly valid tools for the risk management of nanomaterials was deemed important. This could solve the existing challenges in the field.

In addition to this, promoting safe design principles for nanotechnology by minimizing possible risks in the design stages would be a great help. Therefore, due to the expansion of existing knowledge related to the dangers of nanomaterials, this framework should be continuously able to be adapted to new developments and innovations in nanotechnology, in accordance with needs and expectations.

We aimed to provide a method to identify and evaluate the health risks of nanomaterials and providing a decision-support platform to facilitate the decision-making process in occupational risk management in workplaces, could be effective in selecting and implementing appropriate and applicable control measures.

The study presented a comprehensive framework for assessing and managing the health risks associated with nanomaterials. However, it is essential to acknowledge the limitations further studies. There is this need to update the classification of risk and exposure to comply with the latest toxicology discoveries regarding newly manufactured nanomaterials. Additionally, while the framework provides a systematic and applicable method for companies, laboratories, and government institutions to evaluate nanomaterial health risks and facilitate decision-making, it may not entirely eliminate the need for expensive and complex exposure assessment techniques.

Furthermore, the decision tree component of the framework is designed to be utilized in cases where information is insufficient, which highlights the need for conducting comprehensive toxicological studies to create and update the database for nanomaterials. This would not only strengthen the framework but also contribute to the broader understanding of nanomaterial hazards.

Naziri et al. (2024) highlighted the potential development of structured frameworks and practical tools to support policy-making and workplace safety [44]. Future research endeavors should focus on evaluating and validating the proposed framework in real-world working environments involving nanomaterials. Such studies would provide valuable insights into the practical implementation and effectiveness of the framework, as well as the proposed control measures. Addressing these limitations and expanding the scope of the framework will contribute to a more comprehensive understanding and effective management of the risks associated with nanomaterials.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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