



# Advancements of Nanotechnology and Nanomaterials in Environmental and Human Protection for Combatting the COVID-19 During and Post-pandemic Era: A Comprehensive Scientific Review

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## Abstract

In December 2019, an outbreak of unknown pneumonia emerged in Wuhan City, Hubei Province, China. It was later identified as the SARS-CoV-2 virus and has since infected over 9 million people in more than 213 countries worldwide. Massive papers on the topic of SARS-CoV-2 that have already been published are necessary to be analyzed and discussed. This paper used the combination of systematic literature network analysis and content analysis to develop a comprehensive discussion related to the use of nanotechnology and materials in environmental and human protection. It is shown that various efforts have been made to control the transmission of this pandemic. Nanotechnology plays a crucial role in modern vaccine design, as nanomaterials are essential tools for antigen delivery, adjuvants, and mimics of viral structures. In addition, nanomaterials and nanotechnology also reported a crucial role in environmental protection for defence and treating the pandemic. To eradicate pandemics now and in the future, successful treatments must enable rapid discovery, scalable manufacturing, and global distribution. In this review, we discuss the current approaches to COVID-19 development and highlight the critical role of nanotechnology and nanomaterials in combating the virus in the human body and the environment.

**Keywords** Nanomaterial · Nanotechnology · SARS-CoV-2 · COVID-19

## Introduction

In December 2019, an unknown pneumonia was confirmed in Wuhan City, Hubei Province, China. This unidentified pneumonia was later known as a novel coronavirus called SARS-CoV-2 and the disease caused by this virus is called Covid-19 (coronavirus disease 2019) spreading to many countries. In January 2020, the World Health Organization

(WHO) declared a global emergency due to the rapid spread and increasing number of cases in China. As of now, it has infected more than 213 countries [1].

The COVID-19 pandemic poses a significant challenge for researchers to find solutions as soon as possible. Studies have shown that SARS-CoV-2, the virus causing COVID-19, can be found in various environments, such as specimens, blood, faeces, and solid waste from infected patients [2]. The use of single-use plastics for personal protective equipment (PPE) has also led to a significant increase in plastic waste production, contributing to the growing problem of chemical waste [3]. The proper treatment of solid waste produced during the pandemic is essential, especially in developing countries where waste is often not treated according to established protocols. A recent study in Wuhan, China, showed that various disinfectant strategies, such as ozone, ultraviolet irradiation, and chlorine-based solutions, were effective in eliminating SARS-CoV-2 [4]. However, these technologies are costly, requiring expert operators and high energy consumption.

Nanotechnologies and nanomaterials have been used successfully as alternative materials for wastewater treatment,

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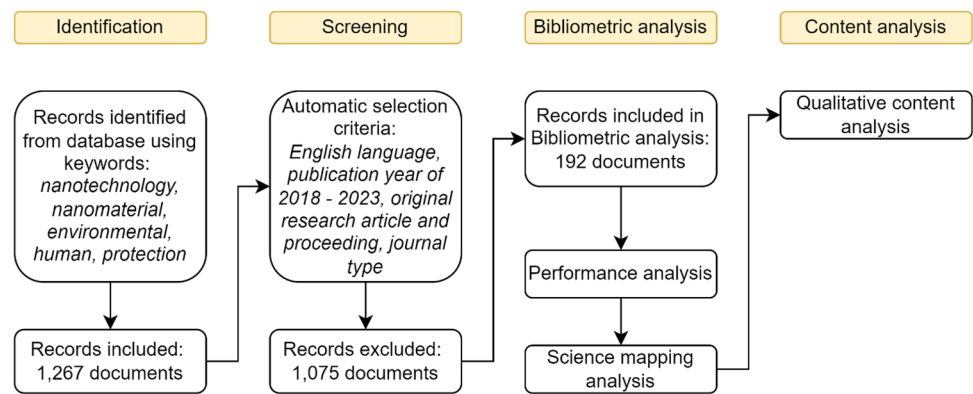
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**Fig. 1** Research methodologies

soil remediation, and air pollution control [5]. While there is no evidence of their effectiveness in eliminating viruses in the environment, combining nanotechnology and medicine shows potential. For example, a medical study reported that chloroquine, combined with nanoparticles, could inhibit the endocytosis process and potentially be used to treat COVID-19 patients [6]. While there are currently no published papers on using nanotechnology and nanomaterials to eliminate SARS-CoV-2 in the environment, there is potential for modifying these materials for environmental remediation during the pandemic.

Combining a chemical activator with a disinfectant may offer a promising approach for developing novel materials to remediate the environment during the COVID-19 pandemic. This review aims to identify the potential of nanotechnology and nanomaterials in combatting the pandemic, while highlighting the challenges and opportunities associated with their use. By providing insights into this exciting field, we hope to inspire further research and development in this field. Therefore, this review will be beneficial for researchers and diagnostic experts who aim to use or develop nanomaterials and nanotechnology for defending, treating, or combatting COVID-19.

## Methods

This paper used the combination of systematic literature network analysis (SLNA) and content analysis to develop a comprehensive discussion related to the use of nanotechnology and materials in environmental and human protection. This hybrid review is considered as practical and in-depth enough to develop a good literature review and get a faster content analysis compared to systematic literature review (SLR) or bibliometric analysis (BA) alone [7]. The SLNA is used to understand the current and past research trend, identify the most interesting topic in the field and analyze the potential gaps for future research direction [8]. Meanwhile, the content analysis was used to develop in-depth discussion

in the recent advancements of the topic and deepen understanding of several materials that has been developed by researchers around the world [9]. The study began with metadata collection using PRISMA 2020 protocols and network analysis using bibliometric analysis [9]. Then, qualitative content analysis was employed. The detailed instruction of the methodology is explained for enabling any replication for this paper in the future (Fig. 1).

## Data Collection

In this following section, we first describe the stages of employing systematic literature review protocols for selecting and evaluating the metadata related to nanotechnology and materials in environmental and human protection. As it is previously described, the procedures of collecting data were conducted based on PRISMA 2020 protocols which was written by Page et al. [10]. PRISMA 2020 protocols is the basic theoretical foundation for developing a good systematic review. First, identification of the research opportunity in the field was justified by analyzing the relevance and understanding the importance of the research topic through the broadest analysis of many related scientific papers [11]. Then, data collection was done by choosing the research database and papers where the metadata selection took place. We used *Scopus*® database as this database is accessible by the authors. Therefore, *Scopus*® is also a multidisciplinary abstract and citation database for many scientific literatures worldwide. After choosing the database, several steps included for the SLNA, which consists of (1) the identification of the metadata related topic via databases and registers, (2) screening the records automatically by using the automation tools and assessment of the eligibility of the documents, and (3) inclusion of the studies for further analysis. We limited the search of database to the manuscript indexed before April 9, 2023.

During the metadata identification, selecting appropriate keywords becomes the most important thing to do first. In this study, we used two combinations of keywords, which

the first was *nanotechnology* AND *nanomaterial* AND *environmental* AND *human* AND *protection*. We found 1267 documents for this effort. The keywords selection was followed by automation filter to limit the paper selection, then reducing the number of papers that is relevant to our research goals. Several inclusion criteria including the language, publication year, document types, and source types were added to cut the amount of metadata. The language was chosen as English, the document types was limited to original research article, and conference proceeding, and the source types was restricted to journal. Those restriction criteria were applied since we need to ensure the accessibility of each manuscript for further qualitative content processing. The publication year was limited to only from 2018 to 2023 as we want to know the pattern of the research related to the topic during the three period: before (2018–2019), during (2020–2021), and after COVID-19 outbreak (2022–2023). After several restrictions by automation tools, we got 192 metadata of the documents. Finally in the inclusion phase, the comma separated value (.csv) format of those metadata was extracted to be analyzed in the bibliometric and content analysis for developing the current research trends, gaps, and in-depth analysis.

## Data Analysis

In the bibliometric analysis, we followed Song et al. concept to perform the performance and science mapping analysis. The performance analysis assesses the different parameters such as the journals, countries, and institutions [12]. Very principal indicators for this analysis are the counting of the number of articles or the quantity of the research and citations which refer to the quality of the research. We used VOSviewer and Excel software to develop co-authorship, citation, and co-occurrence keyword mapping. VOSviewer software is an open-source platform that can be used to visualize scientific landscapes easily [13]. The minimum threshold for the number of documents of a country and occurrences of a keyword in the co-authorship analysis and co-occurrence keyword was set to 2. Several scientific maps are generated using the help of software.

For bibliometric analysis especially through the title and abstract, Orange Data Mining software as a powerful open-source platform for big data analysis and visualization [14]. A set of text mining analysis in the Orange Data Mining was used to perform the bibliometric analysis based on the title and abstract. Text mining is the automated extraction which can make unstructured data text become structured information, whereas bibliometric is the statistical approach to analyze the current research trends and patterns in the metadata. Both of those approaches are really useful in SLR which sometimes overlap, but have the same pattern to summarize

information and identify the relationship between literatures to gather new scientific concepts [15].

Word cloud was generated using Orange Data Mining software to give additional information related to the most occurrence words in the metadata. The bigger the size of the word, indicating the bigger frequency of the words in the corpus [16]. Therefore, this widget can be used as a preliminary statistic, to monitor the effect of preprocessing in the bag of words. The corpus dataset was preprocessed by several preprocessors such as transformation (lowercase, remove accents, and parse html), tokenization (Regexp), and filtering (stopwords in English, numbers, regexp, and document frequency relative to 0.10–0.90). Topic modelling is used as the tools to analyze and identify which topics are the most interesting, discussed, and debated in the dataset [17]. The model to generate the hidden semantic structure is shown in Fig. 2. The title and abstract of the collected papers were used to find the topics. Latent Dirichlet Allocation (LDA) was used as the generative statistical models in this study since LDA is easily interpreted and doesn't have negative value. Multidimensional scaling (MDS) was used to observe the similarities between the generated topics [18]. Boxplot, scatterplot, and data table are used to visualize the relationship between the chosen topics.

Qualitative content analysis was employed for in-dept analysis of the topic of nanotechnology and materials in environmental and human protection. Therefore, we followed Mayring et al. to develop the framework and procedures of qualitative content analysis. We used mixed procedures between inductive and deductive category principal for defining, summarizing, extracting, and synthesizing new concept through literature survey [19]. Based on previous review works, content analysis can be used as a strong methods to filling up the method gaps of bibliometric review methods.

## 3. Research Overview

### Performance Analysis

In this part, we explain the result of the performance analysis using VOSviewer and Excel software. The analysis indicators consist of the number of publications, the number of affiliation country, and occurrences of keywords. Based on the collected metadata, the number of published documents related to the topic of nanomaterials and nanotechnology on environmental and human protection are increase dramatically in 2018–2019. Then, a slight decrease can be found in 2020–2021 which indicates the shift and shock of the worldwide researchers during COVID-19 outbreak. During 2021–2022, the number of research increased a bit but may increase again until the end of 2023. The biggest and the

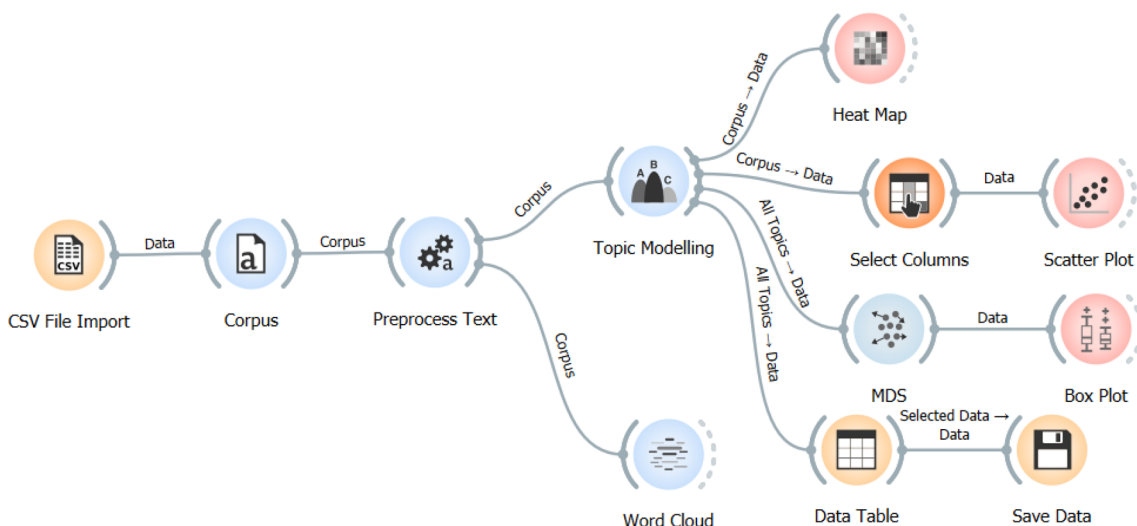


Fig. 2 Topic modelling through the corpus: Title and abstract

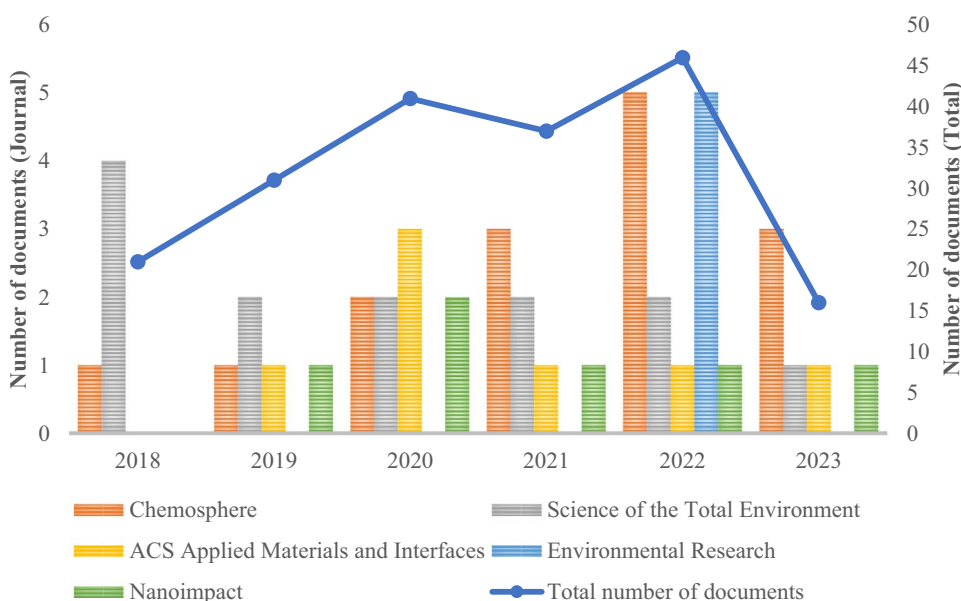
most productive journals publishing documents related to the topic is chemosphere, followed by Science of the Total Environment, ACS Applied Materials and Interfaces, Environmental Research, and Nanoimpact (See Fig. 3).

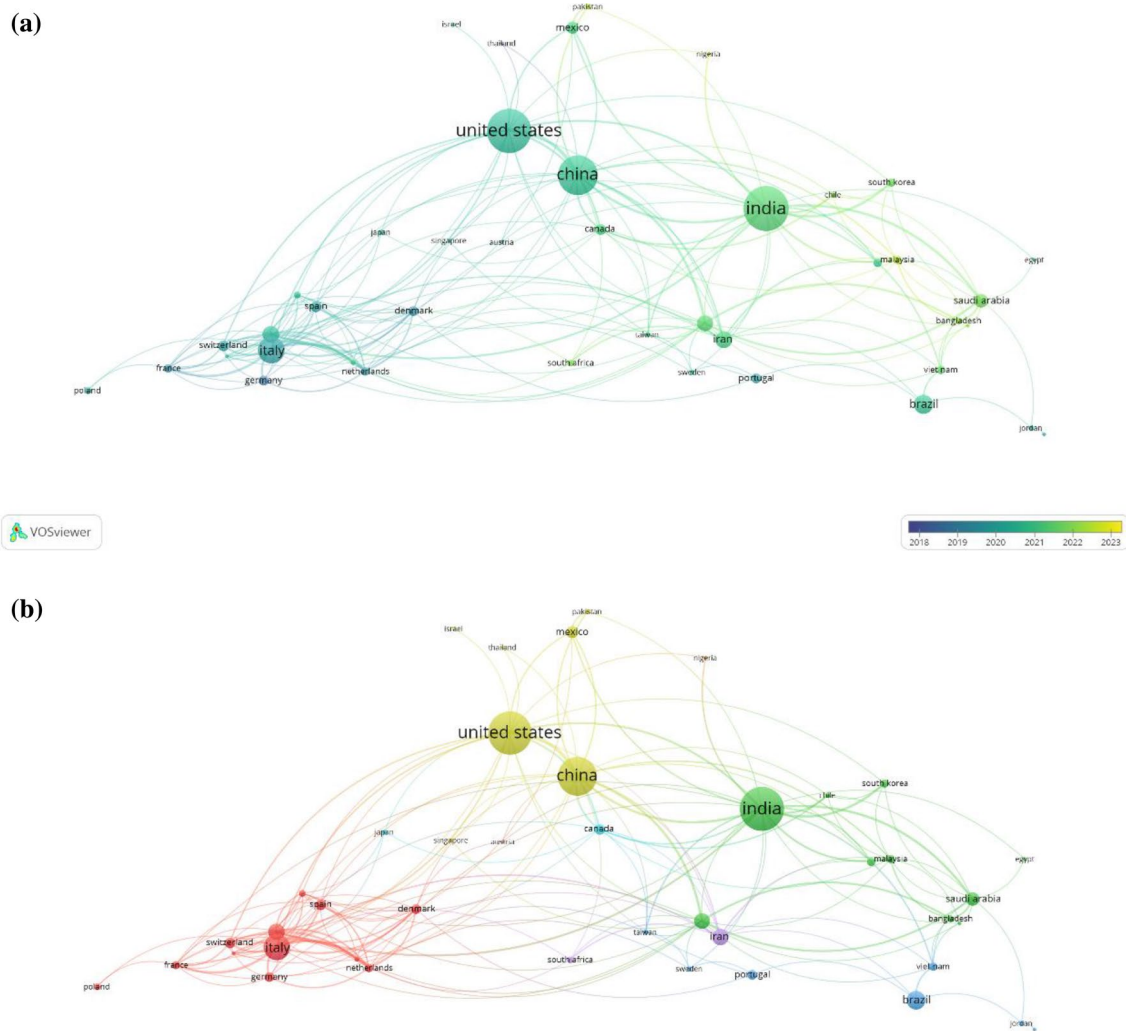
As can be seen in Fig. 4, From the total of 192 articles, there are 58 countries found, and 42 meet the thresholds. The biggest contributor of the study on nanotechnologies and nanomaterial in human and environmental protection is India (40 documents), then followed by United States (32 documents), China (34 documents), Italy (21 documents), and Brazil (14 documents). The oldest publication can be found in the European countries such as France, Germany, Denmark, and Bulgaria, while the newest publication found in the Asian countries such as Malaysia, Bangladesh,

Pakistan, and Saudi Arabia. During the COVID-19 outbreak (2020–2021), the US, China, and India are the leading countries who studied about the topic. There are seven clusters generated from the co-authorship countries which indicate the affiliation countries which are connected between the documents. The biggest cluster was found in yellow and green cluster. While the yellow cluster is centered in United States and China, the green clusters is focused on India. Probably, due to the biggest cases of COVID-19 and the biggest populated countries are found in that area, the number of documents can be higher than other countries.

From Fig. 5, some information can be extracted from the mapping. Of the 685 keywords, 78 meet threshold and 5 items are not shown because it is not connected with the

Fig. 3 Documents by year to the related topic and top five journals publishing the research paper related to the general topic





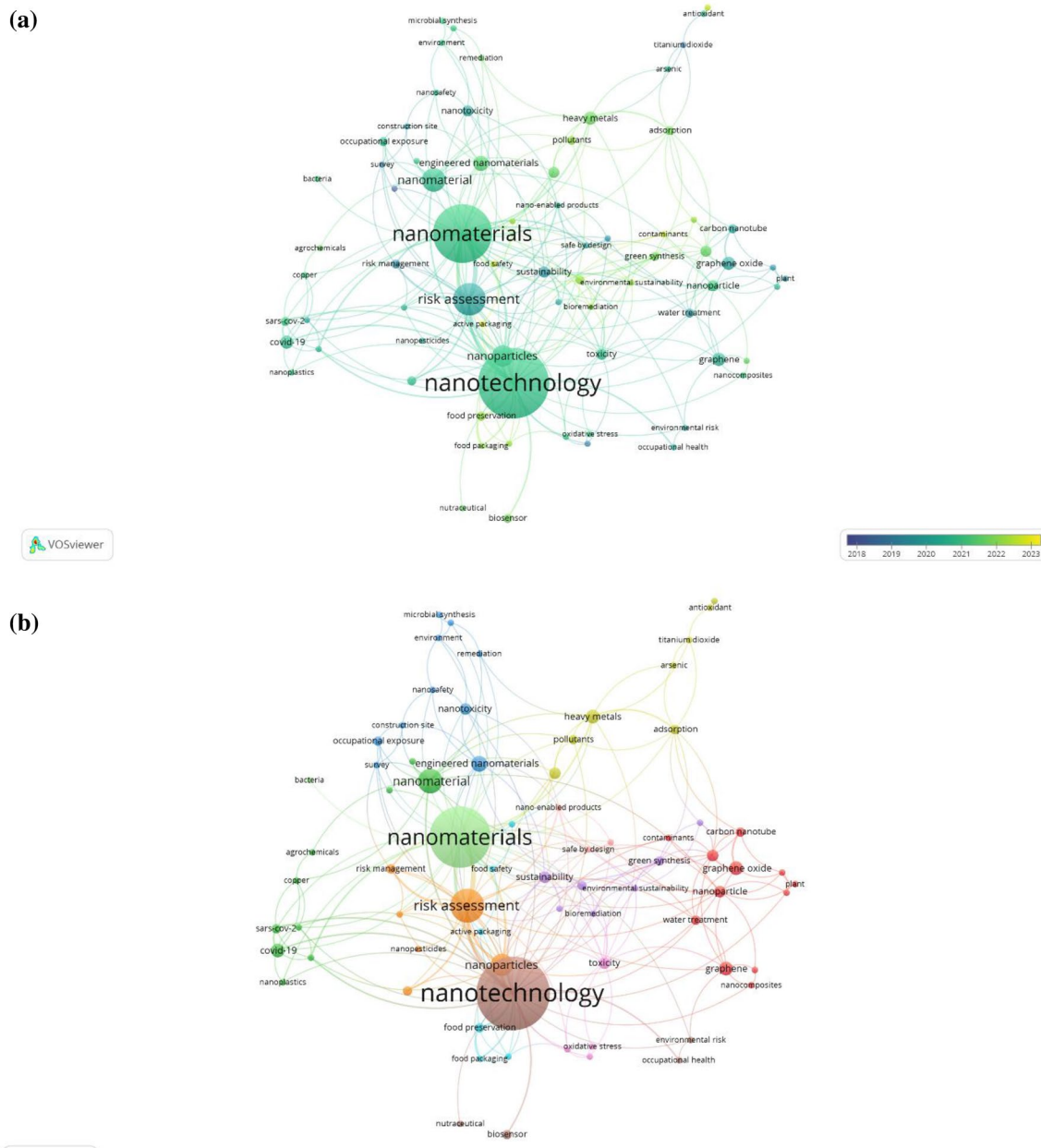
**Fig. 4** Co-authorship based on affiliation countries: **a** Overlay and **b** network visualization

largest set of connected items. The oldest keywords in the set of metadata are found such as “risk assessment”, “nanotoxicity”, “nanosafety”, and “risk management.” This result indicates that the oldest keywords, especially in the year before COVID-19 outbreak, are focusing on the risk evaluation caused by the production of nanomaterials and nanotechnology. The newest publication which indicates the year after pandemic is determined on food engineering and biochemistry research based on the keywords, such as “food packaging”, “food preservation”, “food safety”, “food pollutants”, “green chemistry”. During the outbreak, the researchers are focusing on the human prevention of the spreading of coronavirus. It is also indicated by the occurrence several terms such as “SARS-COV-2”, “COVID-19”, “nanovaccines”, “engineered nanomaterials.” There are 11 clusters that can be generated in the set of keywords. The biggest keywords are found in the red cluster, while it is indicating the use of nanotechnology and nanomaterials in the water

and wastewater treatment as environmental protection. The second cluster can be found in the green cluster indicates the use of nanomaterials for human protection from COVID-19. This finding is interesting since the use of nanotechnology is focusing on such themes.

### LDA Modelling

Before we conducted the LDA modelling, we used word cloud to confirm that the preprocessing activity was done in a good way so then we can model the text using LDA approaches. As can be seen in Fig. 6, several words can be generated from the title and abstract. It appears that beyond the keywords that is used for data collection, the top 5 interesting words that can be extracted are “nanoparticles” (145 words), “applications” (124 words), “food” (114 words), “water” (107 words), and “health” (97 words). There are 10 topics that are derived from the metadata of title and



**Fig. 5** Co-authorship based on affiliation countries: **a** Overlay and **b** network visualization

abstracts as it can be seen in Table 1. Several new topics are shown to be generated using previous text mining by VOSviewer.

From the marginal topic probability (MTP) shown in Fig. 7., the biggest value of MTP can be generated in Topic 5 which is environmental risk assessment of nanomaterials and nanotechnology development. The corpus data shows that the biggest trends fall to the environmental applicability of the nanomaterials and technology. Then, topics 10, 8, and 1 are following the biggest topic that can be generated. The topic is focused on the use of nano-based products for

environmental protection and food sensing, and specifically the employment of carbon-based material. Besides, the lowest MTP values is shown in the Topic 3 which is about the use of nanomaterial for plant development. This could be the research gaps for further interventions (Figs. 8).

Based on MDS results, there are similarities between Topic 1, 4, and 9. This is also confirmed using the result presented in Table 1. The result showed that all topics are generally discussed about the use of nanomaterials and technology for the environment. The Topic 1 and 9 even almost similar where the difference is only about the effect



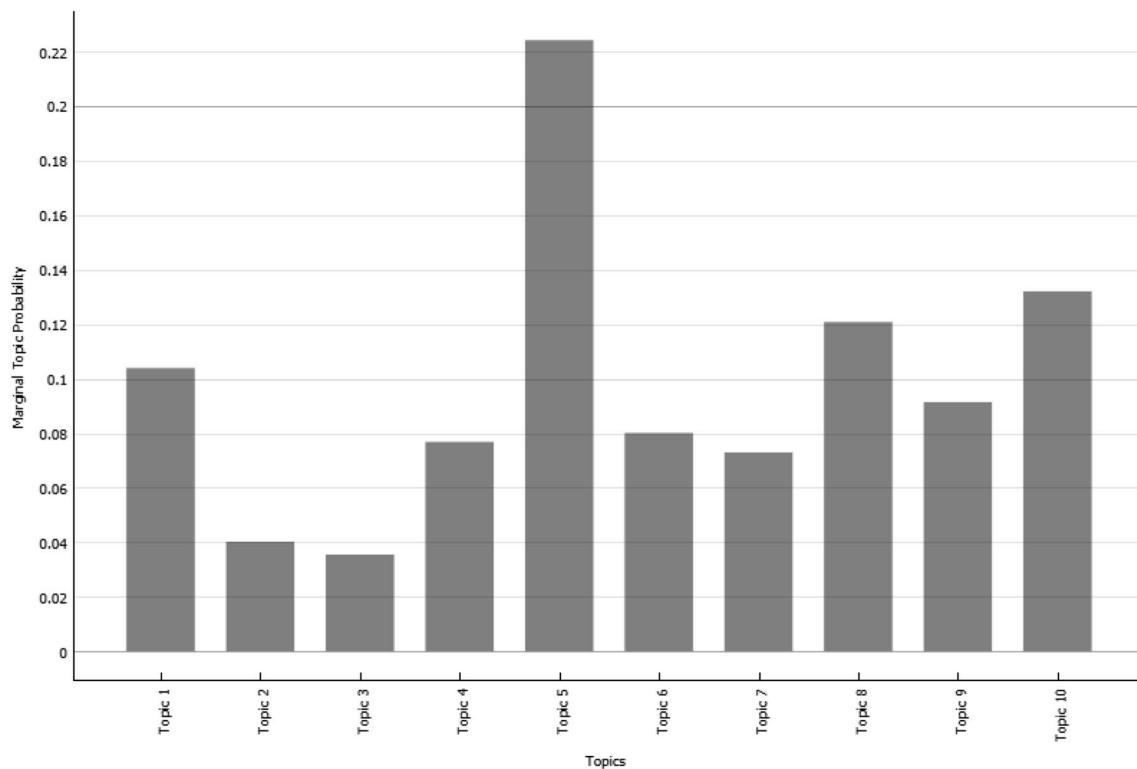


Fig. 7 LDA results

application related to the topic itself. However, to confirm this all-statistical analysis, further in-depth analysis should be done to get a comprehensive view of the research core.

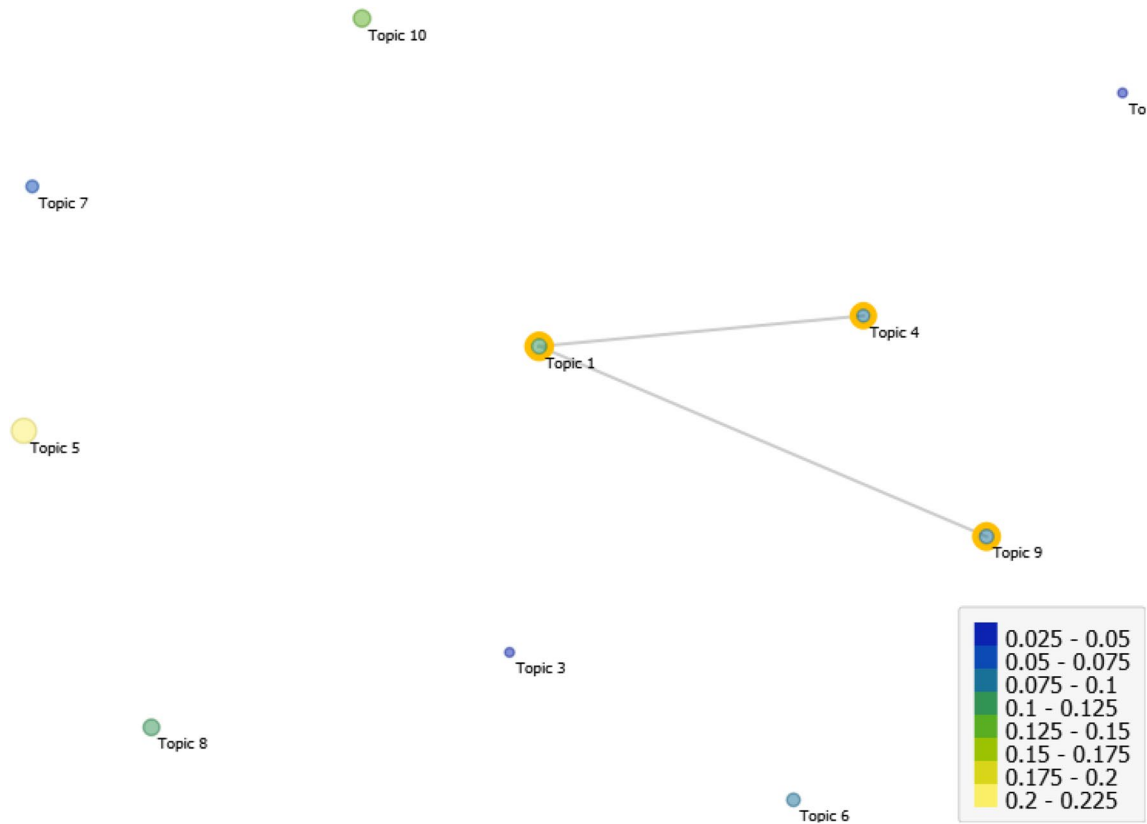
## SARS-COV-2 and Post-pandemic Overview

In December 2019, China Health Authority alerted the WHO about unknown pneumonia in Wuhan City, Hubei Province. The first case was reported on 8th December 2019 from Traditional Huanan Seafood Market. In January 2020, WHO abbreviated coronavirus as 2019-nCoV, and the disease was named COVID-19 (Coronavirus disease 2019). This virus is a pathogen that attacks the human respiratory and is called severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). According to WHO, 9.93 Million people were confirmed positive for COVID-19 around the world (25th June 2020); since December 2019, more than 481 thousand people were dead, and 4.72 million have recovered. This pandemic has been spreading to more than 213 countries around the world. The USA is one of the most significantly infected people around the world. More than 2.4 million people in this country were infected with new cases, more than 39,000 each day (data available on <https://www.worldometers.info/coronavirus/>).

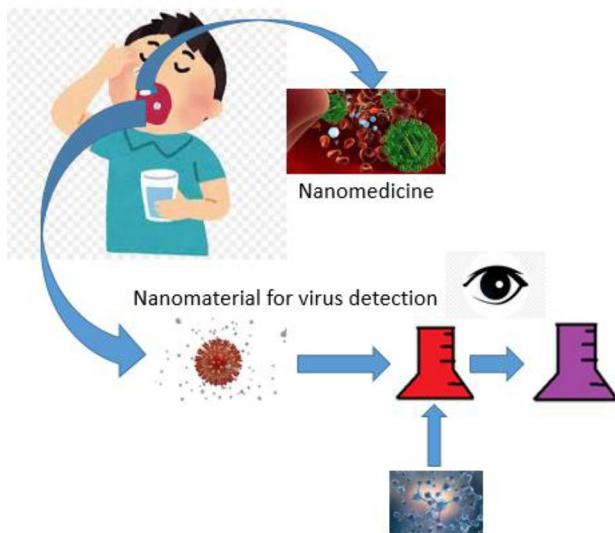
SARS-CoV-2 is a member of *Coronaviridae* and *Nidovirales*. These families consist of two sub-families, *Torovirinae* and *Coronavirinae*. The family of *Coronavirinae* was subdivided into four genera, such as Alphacoronavirus. This virus is a human coronavirus, two of the identified human coronavirus (HCoV) are HCoV-NL63 and HCoV-229E, the second genera of *Coronavirinae* are Betacoronavirus includes HCoV-OC43, SARS-HCoV (Severe Acute Respiratory Syndrome Human Coronavirus), MERS-CoV (Middle Eastern respiratory syndrome coronavirus) and HCoV-HKU1. Gamacoronavirus includes viruses of birds and whales, and the last is Deltacoronavirus, including viruses isolated from birds and pigs. SARS-CoV and MERS-CoV is not more pathogen than SARS-CoV-2; this virus has + ssRNA (single-stranded RNA) virus [20].

SARS-CoV-2 is a pathogenic virus with a genome indicated to two bat-derived-SARS-like 2018 coronaviruses in eastern China (Bat-SL-COVZXC21 and bat-SL-CoVZC45) and 79% similar to MERS-CoV [21]. Another detected coronavirus caused by bats was confirmed in Yunan Province (92% genome sequence identity). This virus is called Bat-CoV RaTG13 [22]. A recent study informed that there is no evidence of recombination of the SARS-CoV-2 genome from original viruses from the bat (i.e., SARSr-CoVs, Bat-CoV RaTG13, and SARS-CoV). Thus, a study is needed to analyze an intermediate host who transmitted this virus





**Fig. 8** MDS map



**Fig. 9** Nanotechnology and nanomaterial for nanomedicine and virus detection

to humans. The first study assumed that Huanan Seafood Traditional market is the first place where this virus found. In this place, the researcher assumed that SARS-CoV-2 was

transmitted from animals to humans. However, a genomic study has provided a shred of evidence that this pneumonia was transmitted from another, no one confirmed that this virus is spreading from Huanan Traditional Market in December 2019, first.

According to the isolated patient of COVID-19 from Wuhan Traditional Seafood Market, the genome of Wuhan-Hu-1 coronavirus (WHCV) was detected. The detected strain of SARS-CoV-2 is 29.9 kb, while MERS-CoV and SARS-CoV have a positive-sense of the RNA genome of 27.9 kb and 30.1 kb [23]. The ACE2 was founded in the respiratory cell from the infected patient with COVID-19. It is also known as the receptor for SARS-CoV and regulates of human to human transmission and cross-specimen [24]. A research institute in China confirmed the diagnostic criteria for SARS-CoV-2. The key to the detection of SARS-CoV-2 is nucleic acid detection in the nasal and throat swab sampling or respiratory track sampling by real-time PCR. On 7th January 2020, the tested virus from infected people from Wuhan informed us that the virus has more than 95% homology with bat coronavirus and 75% similarity with SARS-CoV. This paper also confirmed that environmental samples from Huanan Traditional Marker also tested positive and told the virus urinated from there [25]. After 1st

January 2020, China confirmed the person to person transmission. This transmission of SARS-CoV-2 is direct contact, possible aerosol transmissions, and droplet. Human sneezes cough, talks or laugh, aerosol or droplets are generated and fall from the mouth due to gravity [26]. The transmission of SARS-CoV-2 from the material (i.e., door, window, table, and many more) was founded. The aerosol and droplets from infected people maybe attach to goods and become a SARS-CoV-2 transmission. In addition to the transmission caused by physical contact, research on the transmission of Covid-19 in pregnant women to their babies is interesting to study. A recent study informed that a total of 31 infected pregnant moms with COVID-19 showed no COVID-19 infection in their placentas or neonates [27]. Unfortunately, samples of this research are limited, and two of the samples were died due to respiratory complications. Transmission of COVID-19, also reported by fecal–oral, independent laboratories from Wuhan, China, declared that they have successfully isolated infected patients infected from the digestive system. This fact informed that SARS-CoV-2 could infect people through the digestive system [28].

A recent study informed that by sampling, 1099 confirmed cases in the laboratories from China. The typical clinical manifestation of positive COVID-19 is fever (88.7%) and cough (67.8%). Shortness of breath (18.6%), fatigue (38.1%), production of sputum (33.4%), headache (13.66%), and sore throat (13.9%) [29] and part of patients manifested vomiting (5.0%) and gastrointestinal symptoms with diarrheal (3.8%). This data confirmed consistency with previous data in Hubei Province, where fever and cough are the dominant symptoms [30]. Based on the current situation, the critical condition of patients always shows symptoms of complications such as severe illness, acute respiratory distress syndrome (ARDS), shock, arrhythmia, acute cardiac injury, acute kidney injury, liver dysfunction, and secondary infection. A recent study also showed that elderly patients with ARDS and comorbidities showed a higher death risk [30].

The incubation period of SARS-CoV-2 is estimated to be between 3 and 7 days or range 2–14 days for long transmission. The necessary reproduction number of SARS-CoV-2 estimates ranged from 1.4 to 6.49 with a mean of 3.28. This value is more prominent than SARS-CoV (the reproduction number of SARS-CoV is 2–5). Several treatments were treated to solve this pandemic. The possible treatment for SARS-CoV-2 is general, antiviral therapy, cellular therapy, immunotherapy, and traditional Chinese medicine. General treatment is the treatment with general activity such as bed rest, maintaining and ensuring sufficient energy. This treatment should use monitoring vital signs such as pulse, heart rate, oxygen saturation, blood pressure, and respiratory rate). The second treatment is antiviral therapy, including interferon-alpha, lopinavir/ritonavir, ribavirin, chloroquine,

arbidol (umifenovir), and remdesivir. The third therapy is cellular therapy, including natural killer cells and mesenchymal stem cells (MSCs), and the fourth therapy includes immunotherapy, including convalescent plasma therapy and monoclonal antibodies [31]. The definitive therapy is Chinese traditional medicine that uses glycyrrhizin as an active component of the root. Glycyrrhizin reported successfully to treat positive SARS [31]. This material also can bind ACE2 with potential anti-COVID-19 effect. Another one of traditional medicine from China is quercetin. This material also reported the antiviral effect by inhibiting the 3C<sub>1</sub>pro of SARS-CoV [32] and successfully blocked the entry of SARS-CoV into host cell [33].

In post-pandemic era nanotechnology and nanomaterials reported the crucial role for predict and defence of new pandemic using nanosensor [34]. Strategy for synergy of prevention, detection and diagnosis reported by nanomaterial sensor such as silicon, nanowires, p-type Si nanowires and n-type Si nanowires [34]. Another sensor that need to develop in post-pandemic condition are chemical sensor, gas sensor, DNA sensor, electro-chemical sensor, and optical sensor [34]. These sensors need to develop due to their powerful abilities for viruses detection. Thus, when the virus can be detected before spreading as pandemic, the pandemic can be hold.

## Overview of Nanotechnology for Manage the SARS-CoV-2 During and Post-pandemic

Nanotechnology and nanomaterials have the potential to manage the pandemic. Detecting infected viruses quickly is crucial in stopping the spread of the pandemic. The complete sequence of the SARS-CoV-2 genome was determined and shared globally, aiding in the development of vaccines and medicines. Cryo-electron microscopy was used to characterize the nanoscale features of the virus. Traditional lab-based tests for measuring antibody levels and viral load have been in high demand, leading to an emphasis on point-of-care and self-administered rapid antigen testing using nanoparticles like colloidal gold [35]. Nanopore-based sequencing techniques and nanomaterial-based sensors have also been developed for virus detection [36]. These advancements have allowed for timely identification of asymptomatic cases in various settings, including healthcare.

Nanotechnology has emerged as a promising tool for managing the SARS-CoV-2 virus during and after the pandemic. One of the critical challenges in controlling the pandemic has been rapid and accurate detection of the virus. Nanotechnology can help in this aspect by enabling faster and more sensitive virus detection. For example, traditional lab-based tests for measuring antibody levels and viral load, such as RT-PCR [37], have been in high demand during

the pandemic. Therefore, greater emphasis has been placed on point-of-care and self-administered rapid antigen testing using nanoparticles such as colloidal gold. In addition to virus detection, nanotechnology can also aid in the development of effective therapeutics and vaccines. Nanoparticles can be used as drug carriers to deliver drugs directly to the site of infection, reducing side effects and increasing efficacy [38]. Nanoparticles can also be used to improve the stability and immunogenicity of vaccines, increasing their effectiveness [39, 40].

Nanotechnology can also help in developing effective disinfection strategies to prevent the spread of the virus. Nanomaterials such as silver nanoparticles and copper oxide nanoparticles have been found to have potent antimicrobial properties and can be used as disinfectants [41, 42]. Furthermore, nanotechnology can help in the development of robust and reliable diagnostic tools and sensors for the early detection of future pandemics. Nanopore-based sequencing techniques and nanomaterial-based sensors have already been developed for virus detection, and further advancements are expected in this field. Overall, nanotechnology has the potential to revolutionize the way we manage pandemics like SARS-CoV-2, enabling faster and more effective detection, prevention, and treatment of infectious diseases.

Various types of nanoparticles, such as colloidal gold nanoparticles, quantum dots, rare earth nanoparticles, magnetic nanoparticles, and carbon nanotubes, can be utilized in immunoassays for detecting different targets. These tests can use samples from nasal swabs, throat swabs, sputum, saliva, or serum. As of May 2022, there are 49 US FDA-approved antigen diagnostic devices for COVID-19, most of which are colloidal gold nanoparticle-based Lateral Flow Assays (LFAs). In immunological assays, different nanoparticles are coupled with antibodies to either produce a visible color change or allow for fluorescent, electrochemical, or magnetic signal detection when the conjugated antibody binds to the antigen. Colloidal gold nanoparticle based LFA is the most common type, providing the benefits of low cost and an uncomplicated method for reading results. The fluorescence-based detection method uses fluorophores such as quantum dots and rare earth nanoparticles, which offer higher sensitivity and a lower detection limit compared to colorimetric detection. QD-based fluorescence assays can achieve at least 10 times higher sensitivity than gold-based ones. However, specific fluorescence reading instruments are needed for reading the results. Magnetic LFA is another method for antigen testing, measuring the stray field changes from the magnetic nanoparticles, offering high sensitivity and low detection limits due to no or negligible background noise. Nevertheless, specific instruments such as giant magnetoresistance sensors are needed for detection and are thus not widely used yet. Recently, hybrid nanoparticles such as QD-loaded mesoporous silica-based LFA could enhance

detection sensitivity by up to 104 times compared to commercial colloidal gold-based LFA and may, therefore, be used for early detection of SARS-CoV-2 infection. Table 2 informed the nanomaterials and nanotechnologies commonly used in treating, detection and defeat viruses.

## Nanotechnology and Nanomaterials Before and During Pandemic

In recent decades, research on nanotechnology and nanomaterials has been developing in various countries. Nanotechnology has a broad range of applications, including semiconductor chips and microelectronics, ceramics, metal oxides, lighter-weight alloys and metallic compounds, fuel cells, batteries, purification, pharmaceuticals, and enzymes. In the medical field, nanotechnology is being used to develop drug delivery systems that can specifically target cancer cells. Additionally, nanotechnology is being utilized as an alternative method for solving the problem of contaminated soil, sediments, and solid waste [43]. Sorption the contaminants for water and air pollution, oil and water separation [44], destructing of bacteria (i.e., anthrax, E Colli, etc.), and purifying clean water without chlorination [45, 46].

The development of nanotechnology in environmental issues includes treatment and remediation. The EPA has been developing nanotechnology as a treatment-technologies for effectively treat environmental pollutants. Besides, EPA was also developing this technology as a remediation technology for environmental pollutants [47]. Several international organizations put close attention to this issue, such as The Federal Water Pollution Control Act (FWPCA), the Marine Protection, Research and Sanctuaries Act (MPRSA), the Safe Drinking Water (SDWA) and the Oil Pollution Control Act (OPA). These organizations were put on international congress in 1977, renamed the FWPCA the Clean Water Act (CWA), and substantially revamped and revised the control of toxic water pollutants. In recent decades, nanotechnology and nanomaterials have been developing. The extraordinary feature and novel properties of nanomaterials are metals, ceramics, metals oxide, polymers, and modified carbon materials (i.e., fullerenes and carbon nanotubes), even this material also developing into Fanta black. The development of nanotechnology and nanomaterials is about modifying metals, iron, aluminum, nickel, silver, gold, copper, silica products, mixed oxide, iron oxide, zinc oxide, titanium, and aluminum dioxide.

The nanomaterial was produced by high-temperature processes (i.e., plasma-based and flame-hydrolysis), chemical vapor deposition (CVD), sol-gel processing, electrodeposition, mechanical crushing via high-energy ball milling, and naturally occurring materials [48]. One of the robust materials used for wastewater treatment is carbon nanotubes and

**Table 2** Nanomaterials/Nanotechnologies for beating pandemic COVID-19

Material/Nanotechnology	Description	References
Graphene oxide	To make masks that are highly effective at filtering out particles	[75–80]
Silver nanoparticles	An antiviral agent that can help prevent the spread of viruses	[81–87]
Nanoscale copper	To kill viruses and bacteria, making it useful in masks and other protective equipment	[88–91]
Zinc oxide nanoparticles	To kill viruses and bacteria, making it useful in hand sanitizers and other disinfectants	[92–95]
Carbon nanotubes	To make more durable and effective filters for masks	[96–99]
Nanofibers	To make masks and other protective equipment to increase filtration efficiency	[100–103]
Quantum dots	To detect the presence of viruses and bacteria	[104–110]
Gold nanoparticles	To deliver drugs directly to infected cells, increasing the efficacy of treatments	[11, 111–113]
Liposomes	To deliver drugs directly to infected cells and can also be used as vaccine delivery system	[114, 115]
Iron oxide nanoparticles	To be used in diagnostic tests to detect the presence of viruses and bacteria	[116–120]
Nanodiamonds	To make more durable and effective filters for masks	[121, 122]
Antimicrobial coatings	To be applied to surfaces to prevent the spread of viruses and bacteria	[123–128]
Nanosensors	To detect the presence of viruses and bacteria in the air or on surfaces	[12, 34, 82, 100, 116, 129]
Nanoporous materials	To be used in filters to increase filtration efficiency	[101, 103, 130–133]
Fullerenes	To make more durable and effective filters for masks	[10, 134, 135]
Nanorobots	To deliver drugs directly to infected cells	[136, 137]
Natural nanoparticles	To be used as an antiviral agent and can help prevent the spread of viruses	[138, 139]
Titanium dioxide nanoparticles	To make self-cleaning surfaces, which can help prevent the spread of viruses and bacteria	[9, 140–143]
Hydrogels	To be used in masks and other protective equipment to increase filtration efficiency	[67, 144, 145]
Metal–organic frameworks	To be used in diagnostic tests to detect the presence of viruses and bacteria	[43, 146]
Magnetic nanoparticles	To be used in diagnostic tests and as a drug delivery system	[147–151]
Electrospun fibers	To be used in masks and other protective equipment to increase filtration efficiency	[140, 146, 152–156]
Nanowires	To be used in sensors to detect the presence of viruses and bacteria	[157–160]
Nanoscale silica	To be used as an antiviral agent and can help prevent the spread of viruses	[12, 161–166]
Dendrimers	To be used to deliver drugs directly to infected cells	[167–172]
Nanocellulose	To be used to make more durable and effective filters for masks	[129, 173–177]
Nanofluidics	To be used in diagnostic tests to detect the presence of viruses and bacteria	[178–183]
Nanocatalysts	To be used to sterilize surfaces and prevent the spread of viruses and bacteria	[184–192]
Quantum well/ quantum dot structures	To be used in sensors to detect the presence of viruses and bacteria	[193–198]
Nanoscale iron	To kill viruses and bacteria, making it useful in masks and other protective equipment	[12, 113, 162–166, 199–203]
Virus-like particles	To be used as a vaccine delivery system	[144, 204–209]

buckyballs. These materials are a seamless cylinder composed of carbon in a hexagonal arrangement. This material also produced in a single-wall nanotube of multiwall nanotubes. This material has a surface area of more than 1500 m<sup>2</sup>/g and a density of 1.40 g/cm<sup>3</sup> [49]. Carbonnanotubes

and buckyballs are excellent material as adsorbent and coating material [50, 51]. Researchers Huston's Rice University found the buckyballs vaporizing carbon, allowing it to condense and form highly stable crystals composed of 60 atoms of carbon apiece (C-60) [52].

The development of nanotechnology and nanomaterial never be the same after this material found. Advanced composites are one of the expansions of nanomaterials to solve the environmental problem. A combination of polymer-matrix nanocomposite was reported in 2015. This novel material developed for wastewater treatment using membrane technology [53]. Unfortunately, this material has been growing in the lab scale. The progress of nanocomposites as an alternative solution for wastewater treatment has been developing in the lab scale. It was two years since the paper published, no one scientific paper reported the membrane of nanocomposite applied in wastewater treatment. Generally, nanomaterials (ZnO, Ag, Cu, GO, TiO<sub>2</sub>, graphene, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>3</sub>O<sub>4</sub>, zeolite, clay, and SiO<sub>2</sub>) reported enhancing the hydrophilicity of the polymeric membrane. This paper also suggested that membrane nanocomposite must combine with other technologies (membrane bio-reactor, electro filtration, and photocatalyst) [54]. Thus, nanotechnology development must be improved until this technology can be applied in the environmental remediation.

The application of nanotechnology for soil contamination was reported—several nanomaterials used as novel materials to solve pollutants from contaminated soil. Several materials were used: solid lipid N.P.s, liposomes, polymeric N.P.s, gold N.P.s, quantum dots, carbon nanotubes, and dendrimers cerium oxide N.P.s and nanogels [55]. Most heavy metals such as Pb, Cd, As, Cu, Hg, Ni, and many more were containing the soil. These heavy metals can be removed by applying nanotechnology. Colloid and an aqueous slurry of nanoparticles can be removed heavy metals in contaminated soil using gravity or pressure. Adsorptive and reactive materials used to solve heavy metals contaminated in soil, adsorptive materials can remove contaminants from soil using adsorption (due to high surface area and unique structure). A nanomaterial called zero-valent iron reported can solve various pollutants in soil. This material successfully reduces Hg<sup>2+</sup>, Ni<sup>2+</sup>, Cd<sup>2+</sup>, Cr<sup>6+</sup>, and Pb<sup>2+</sup> from contaminated soil [56]. Standard redox potential from heavy metals is a mechanism during the decontamination process. Cd and Zn have more negative redox potential values than zero-valent iron. This treatment can be adsorbed on an iron shell. Besides, Ni and Pb have slightly positive redox potential that can be reduced by zero-valent iron and also can be adsorbed on zero-valent iron nanoparticles [57].

The utilization of nanotechnology was developed to solve the air pollution. A recent study informed that nanomaterial promoted as a novel material for gasses and particulates on the atmosphere. Several types of equipment used to control particulate matter such as gravity settlers, electrostatic precipitators, cyclones, fabric filters, and mechanical collectors [58]. Nanotechnology also used to remove sulfur dioxide from boiler flue gas [59]. Nanomaterial reported as a novel material for absorption and adsorption air pollution. Several

factors for environmental remediation using nanotechnology are availability space, equipment location, maximum allowable emission, adequate utilities, the contribution of air pollution for wastewater and solid waste, and the last is air pollution contribution for plant noise level. In another study, nanotechnology is used as a tool for air quality monitoring. This technology successfully builds a sensitive sensor for very low pollutants in the air (i.e., NO, CO, NO<sub>2</sub>, O<sub>3</sub>). This semiconductor targeted to detected CO in 3 ppm concentration, NO<sub>2</sub> in 50 ppb, NO in 100 ppb, and O<sub>3</sub> in 20 ppb [60].

Nanotechnology has been developing in medical therapeutics. Nowadays, nanotechnology is a potential issue in life science, especially for health care and medicine. A novel material developed as biocompatible nanomaterials for artificial tissues and organs, and novel materials such as alumina ceramics and toughened with nanosized zirconia, these nanomaterials are being developed to extend the life of ceramic hip and knee replacement materials [61]. Nanotechnology and nanomaterials also reported as future medicine, these materials used for orthopedic medical applications. In this field, nanotechnology was used as a bone implantation material, this material used for hip or knee prosthesis and osteointegration. The nanophase carbon fiber compacts are better than conventional carbon fiber for bone cells (material is less than 1 μm) [60].

## Nanotechnologies and Nanomaterials for Environmental Protection in Post-pandemic

The recent study informed that 2D Material is a potential nanomaterial for antimicrobial in post-pandemic era. As the COVID-19 post-pandemic era, there is a need to monitor the effectiveness of current nanomaterials against emerging variants and tailor their properties for specific needs. In silico computational analysis can help to screen antiviral or antibacterial properties of 2D materials by performing docking analysis between pathogens and the materials. The success of mRNA-lipid nanoparticle vaccines against COVID-19 highlights the importance of developing nanotechnology-based delivery vectors, which 2D materials can contribute to. Besides, 2D materials possess photocatalytic and photoactive properties that have great potential in cancer therapy, membrane filtration, and pathogen inactivation. However, there are some challenges to address, such as the lack of standard synthesis techniques, small-scale production, retention time, and the actual mechanism of disinfection. As developments in the antibacterial studies of 2D materials may hold promise for antiviral studies of the same materials, scientists should explore the potential of 2D materials for both applications. Research efforts should also aim to evaluate both antibacterial and antiviral properties of 2D

materials to develop and design novel antimicrobial agents for the future.

In addition, 2D materials also reported can solve the future pandemic in material disinfection. This condition will be helpful for defence the new pandemic after post-pandemic era. Environmental pollutants such as pathogens, organic and inorganic wastes can cause health issues. For instance, *Escherichia coli* (*E. coli*) can cause illnesses and deaths in children globally through contaminated water. Common disinfection methods like UV light, chlorination, and ozonation can be ineffective and costly due to pollution, toxic by-product generation, and high energy consumption. Natural enzymes like peroxidase are also impractical due to poor stability, production cost, and complicated purification. Thus, researchers have explored 2D materials like GO, MoS<sub>2</sub>, and MXenes for their innate antimicrobial properties. These materials have unique properties such as large surface area, stability, catalytic activity, low toxicity, and energy-conversion ability. Researchers have found that 2D materials can induce oxidative stress on pathogens and activate photo-thermal effects through NIR light, making them effective in antimicrobial applications.

## Applied of Nanotechnology and Material for Preventing Virus Transmission

Nanotechnology has been using for semiconductors, nano-material, thin-film, and sensors. These materials were used for electronic, environmental remediation, and medicine. Nowadays, more than nine million people are globally affected by the viral disease (COVID-19). This pandemic causes a severe impact on millions of dead people and human health and socio-economic development. Researchers have been developing antiviral therapy using nanomaterials. Nanomaterials have different morphologies and shapes, due to nanometric size, nanomaterials allow drug delivery through impermeable barriers, high surface area to volume ratio is beneficial for improved efficacy and large drug loads. Increased possibility of personalized therapy and decreases the emergence of drug resistance. The combination of nanotechnology and medicine called nanomedicine. Nanomedicine has been using in several viruses treatment (i.e., Human Immunodeficiency Virus (HIV), Hepatitis B Virus (HBV), Hepatitis C Virus (HCV), Herpes Simplex Virus (HSV), Human Papilloma Virus (HPV), Influenza, Human Parainfluenza Virus (HPIV) and Ebola Virus Disease (EDV)) (Fig. 9).

A combination of nanotechnology and medicine created nano-vaccines. This novel combination has several advantages, such as small size. Thus, it is readily identified by the human immune system, nano-vaccines are better vaccine than conventional vaccines in numbers of the way such as

more stable, nano-vaccines do not need to be transported in cold chambers due to can be lyophilized, and nano-vaccines have a longer shelf life for vaccines than conventional vaccines. One successful nano-vaccines from lipid-based nanosystems for HAV treatment, another one succeed nano-vaccines is liposal based vaccine for the prevention of HBV, and a virosomal adjuvant-based vaccine is administered to prevent influenza. The application of nanotechnology for the detection and treatment of disease was developed, especially for molecular diagnostic nanoparticle used in biomolecular in this field detection system of these nanoparticles based on noble metal nanoparticles (silver and gold) due to their unique physicochemical and optical properties. This material can be synthesized as a single inorganic compound, core shells, or alloys, all of these materials have different shapes and sizes. Based on a previous study, the SARS-CoV-2 can be detected by diagnostic in nucleic acid. A recent study informed the utilization of nanotechnology for diagnostic nucleic acid using non-diagnostic. This technology can be identified as the genome sequencing of pathogens and possible to identify specific DNA fingerprints for strains and organisms.

The diagnostic system using nanotechnology-based on noble metal nanoparticle detection can be done by several techniques such as colorimetric [62], electrochemical [63], fluorescence [64], lateral flow [65], SERS, and others, of the technique have weaknesses and strengths. Utilization of colorimetric reported in 2015. This technology successfully detected influenza A virus using antibody-functionalized gold nanoparticles. In this study, the researcher reported they succeeded to developed colorimetric immuno-sensor based on gold nanoparticles modified with the monoclonal anti-hemagglutinin antibody. They assumed that this technology is a fast, selective detection of influenza A virus and simple, this technology can be detected with naked eyes when the color has been changed from red to purple and quantified with the absorption of spectral measurement [62] Detection of influenza virus also reported in 2016, researchers from Oxford University was developed rapid electrochemical with silver nanoparticles. This technology called the art nano-electrochemical technique. This technique successfully detected a single virus level in real time [63]. Various strategies were developed and combined with nanotechnology, including developing a homogeneous colorimetric assay, one of the applied nanotechnology in medical applications. This technology utilized the UV–Vis spectra behavior of noble metal nanoparticles and is using Au nanoparticles. This technology is the basis of a plethora of colorimetric detection scheme.

Aggregation of nanoparticles may be included by DNA hybridization of DNA crosslinkers, increasing ionic strength and protein scaffolding [66]. Nanotechnology also developed for H5N1 influenza virus detection. This material is

fluorescent aptasensor based on the core–shell nanoparticles metal-enhanced fluorescence. A fluorescent aptasensor system was developed as a sensitive detection for recombinant hemagglutinin (rHA) H5N1 protein in human serum. Combination of guanine-rich anti-rHA aptamers by SELEX immobilized in the AgSiO<sub>2</sub> nanoparticle surface, which performed as a metal-enhanced fluorescence. This nanotechnology reported successfully to investigate the ability of the sensing system to detect rHA protein from the complex matrix [64]. Although this technique reported successfully developing as a detector for the H5N1 virus, but this technique not yet applied for SARS-CoV-2. However, the potential application for SARS-CoV-2 detection may be applied. In recent fact, a patient in Indonesia was dead due to SARS-CoV-2 infection, but the double rapid test showed his negative for COVID-19. These technologies may be developed as a simple, fast, and accurate technology for SARS-CoV-2 detection.

Nanotechnology also reported success as infection disease treatment. Several nanomedicines developed in the world, such as carbon nanotubes and fullerenes, can reduce *E. coli* DH5-alpha, *Vibrio fischeri*, and *Bacillus subtilis* with cell membrane damage mechanism. Nanotechnology also developed with biology to solve the bacterial problem from human health. Combination of nanotechnology, biology, and medicine called biological-based antibacterial nanomedicine. Several nanomaterials in this combination are chitosan nanofiber, targeted drug-carrying phage medicines, and poly-L-lactide nanoparticles. These nanomaterials can solve bacterial infection using mechanisms such as loss of membrane permeability, antimicrobial delivery to the pathogen, and release of antimicrobial protein nisin [67]. As a nanosensor, nanotechnology successfully detected viruses, but we need more than just detected. The potential of nanotechnology utilization for viruses treatment need to be developed. The various study explained about nanotechnology for bacterial treatment in human health. Thus, is that possible to use nanotechnology and nanomaterials as a virus treatment? Utilization of nanotechnology used in HIV treatment. The nanoparticle was used in drug targeting and prolog circulation. This treatment used in antiretroviral therapy (i.e., parenteral/ oral/ pulmonary/ transdermal route), vaccine delivery, and microbicides. However, until 2015 no efforts have been successful in laboratory trials. However, the nanoparticles platform shows promising results. Research of nanoparticle to solve virus infection has been developing. The research from this field includes drug targeting and prolog circulation, drug solubility enhancement, transport across blood–brain-barrier, toxicity reduction and dose reduction, chemotherapy using metallic nanoparticles, gene therapy, immunization, microbicide, and vaccines [68].

A recent study informed that nanotechnology has been using for several diseases caused by virus attack (i.e., HIV,

HBV, influenza, HSV, HPV, and other viruses). HBV is one of disease caused by a virus; this virus attack liver with chronic infection and was approximately more than 240 million people. Current nanotechnology applied for this disease is nano therapy including interferon (IFN)-alpha, lamivudine (Epivir®), pegylated IFN (Pegasys®), entecavir cir (Viread®), tenofovir (Viread®), and telivudine (Tyzeka®) [69]. The application of nanotechnology also reported for HCV treatment. A combination of IFN-Alpha and GNPs with solid binding with hyaluronic acid successfully delivered a nanoparticle medicine for HCV infection. These complex nanomedicine materials were reviewed successfully to deliver medicine and close the virus's gap in as an effort to prevent [70]. The next challenge is how to treat the virus in goods using nanotechnology and nanomaterials. The next challenge for nanomaterial and nanotechnology researchers is developing antiviral and antimicrobial properties based on copper, zinc, and silver in goods to fight COVID-19. A combination of nanomaterial in PPE can help doctors, nurses, and medical assistants to keep safe and fight with SARS-CoV-2. A combination of nanomaterial and nanotechnology with the solution (iodide, chlorine, sulfide, and another liquid disinfectant), which are known for fighting an antiviral effect, could be a helpful world. A recent study informed that the treatment of non-woven, hair cups, and respirators using copper ions could help prevent the unwanted nosocomial virus from medical personnel [71]. In principle, the utilization of nanomaterials (metal ions) could be a potential material to reduce the viability of CoV on their substrates. The common touching surface goods with Cu could be helpful. Moreover, a combination of complex nanomaterial with Cu in polymer matrices could help the tuning of metal release, and at the same time, this combination could minimize the risk of nanoparticle release in the environment. Recent publication informed the utilization of gold nanoparticles in biocompatible polymers showed antiviral activity for HIV-1 and influenza virus such as H3N1, H1N1, and H5N1 [72].

Utilization of nanotechnology for wastewater treatment was reported, several materials such as silver, carbon nanotubes, and titanium oxide are known as an antibacterial for wastewater treatment. The microbial mechanism is diverse, includes photocatalytic production of reactive exigent species that cleave DNA and inactive virus. However, the utilization of nanomaterial for SARS-CoV-2 was not found. Disinfectant strategies for the fight with SARS-CoV-2 are limited to chlorine and ozone utilization. However, this liquid phase of disinfectant only treats the SARS-CoV-2 from wastewater. A combination of nanomaterial with disinfectant (i.e., chlorine, ozone, and others) is the recommendation. Utilization of nanomaterial coating with disinfectant could reduce pollutants (i.e., heavy metals, chemical oxygen demand, and biological oxygen demand) due to high surface area, high pores. This material also could be promoted for

virus treatment due to antiviral and antimicrobial effects from disinfectant. A nanoparticle disinfectant for wastewater treatment was developed in 2015. Research collaboration from the USA and China showed that nanoparticles based on  $\text{TiO}_2$ ,  $\text{NiO}$ ,  $\text{ZnO}$ ,  $\text{SiO}_2$ , and  $\text{Al}_2\text{O}_3$  are potential for disinfectant water treatment system [73]. They tried to adsorb colloid particles from the environment. This process will affect transport, face, viability, or reproduction of viruses [74]. Unfortunately, research on nanomaterials for virus treatment in the environment is limited. Thus, this topic will be a challenge for the researcher to find the best nanotechnology and nanomaterial for fighting viruses, especially in this pandemic, this research will be very beneficial for humans.

## Nanotechnologies and Nanomaterials for Human Health in Post-pandemic

With the widespread use of highly effective COVID-19 vaccines in many countries, there is a concern about the ability to quickly redesign vaccines with nanotechnology when new, more virulent variants emerge. One potential solution is the use of mRNA delivered in lipid nano-carriers, which has several advantages over other types of nanoparticles. Metal nanoparticles, such as selenium and gold, have been investigated for antiviral therapy and have shown promise in delivering antiviral medicines to prevent apoptosis induced by the human influenza virus and reduce membrane fusion caused by MERS-CoV. However, concerns about poor biodegradability exist. Lipid-based nanoparticles, such as liposomes, are attractive for clinical use due to their good biocompatibility and biodegradability. Lipid nanoparticles have been used to deliver antiviral agents for treating various infections, including hepatitis C and B, herpes simplex, and HIV. Additionally, lipid nanoparticles could be used to deliver DNA gene therapies and CRISPR gene-editing therapies. Other types of nanoparticles, including polymer nanoparticles, protein-based nanoparticles, inorganic nanoparticles, and exosomes, could also be useful for future vaccine development. Nanoparticles can also exert their own antiviral actions against multiple viruses by mimicking binding sites. For example, nanosponges have been developed that can bind to and neutralize the SARS-CoV-2 virus, preventing it from infecting cells, and this approach is not expected to be affected by viral mutations.

## Recommendation for Future Research Direction and Limitation

Based on current research and advancements in the field of nanotechnology and nanomaterials for beating pandemics, here are some recommendations and future research

directions are developing more efficient and effective antiviral agents: Nanoparticles, such as silver and graphene oxide, have shown promise as antiviral agents. Further research is needed to optimize these nanoparticles and develop new ones that are even more effective. Creating more durable and effective filters for masks: Nanomaterials such as carbon nanotubes, nanofibers, and nanodiamonds have shown potential for creating more durable and effective filters for masks. Further research is needed to optimize these materials and develop new ones that can filter out even smaller particles. Developing new vaccine delivery systems: Liposomes and virus-like particles have shown potential as vaccine delivery systems. Further research is needed to optimize these systems and develop new ones that can deliver vaccines more effectively and efficiently. Creating self-cleaning surfaces: Nanomaterials such as titanium dioxide and nanostructured surfaces have shown potential for creating self-cleaning surfaces that can prevent the spread of viruses and bacteria. Further research is needed to optimize these materials and develop new ones that can be used in a wider range of applications. Developing nanosensors for detecting viruses: Nanosensors have the potential to detect viruses and other pathogens in the air or on surfaces.

Further research is needed to optimize these sensors and develop new ones that can detect a wider range of viruses and bacteria. Developing nanorobots for drug delivery: Nanorobots have the potential to deliver drugs directly to infected cells, increasing the efficacy of treatments. Further research is needed to optimize these robots and develop new ones that can deliver drugs more effectively and efficiently. In conclusion, nanotechnology and nanomaterials have shown great potential for beating pandemics such as COVID-19. Further research is needed to optimize these materials and develop new ones that can be used in a wider range of applications.

Nanoparticles are potentially harmful because they can circulate throughout the bloodstream and lymph streams, penetrate various cells, tissues, and organs, and interact with macromolecules. This toxicity can damage organs and alter their functions. The physical and chemical characteristics of nanoparticles, such as their size, shape, surface charge, and chemical composition, significantly impact their toxicity. Some nanoparticles are not detected by the body's immune system, leading to their accumulation in tissues and organs and causing severe toxicity or even death.

## Conclusions

The COVID-19 pandemic caused by the SARS-COV-2 virus has become a global problem. This virus is recorded to have caused death in more than 9 million people worldwide and infected in more than 213 countries. Until now, the handling



of the SARS-CoV-2 virus is still limited to the use of disinfectants. Nanotechnology and nanomaterials are technologies that are expected to make a positive contribution to the war against the pandemic and post-pandemic era. The use of nanotechnology is still limited to the virus detection process using super-sensitive sensors. The development of nanotechnology and nanomaterials towards the treatment of solid and liquid waste that has been contaminated with SARS-CoV-2 is still very minimal. Nanotechnology is reported to have been used successfully in the treatment of HIV, HVB, and HVC viruses, research into the use of nanotechnology and nanomaterials in reducing the reactive SARS-CoV-2 virus is highly recommended. In addition, the combination of nanomaterials and disinfectants is the direction of future research in the fight against the COVID-19 pandemic. The resulting combination product is expected to kill the SARS-CoV-2 virus in the environment while reducing other pollutant parameters.

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**Data availability** The metadata that used for this study are available from the corresponding author upon request.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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