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Assessing the Role of Advanced 3D Construction Printing in Alleviating Chronic Respiratory Diseases among Construction Personnel

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A R T I C L E I N F O

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A B S T R A C T

Despite the dangers faced by construction workers, on site the risks associated with inhaling dust and silica often go unnoticed possibly because their long-term effects take years to show. Unfortunately, by the time these effects are recognized lung damage is often irreversible. This study aims to address the issue of diseases among construction workers and explore how 3D printing in construction could potentially reduce the occurrence of these ailments. The research goals included identifying the causes of diseases in construction examining strategies to minimize exposure to dust and silica on site assessing the advantages of 3D printing in reducing such exposure investigating obstacles that hinder using 3D printing for this purpose and exploring strategies to promote wider adoption of construction 3D printing for mitigating long term respiratory diseases among workers. To achieve these objectives a thorough review of literature was conducted along with a survey and interviews with professionals and researchers in the field of 3D printing. These efforts aimed at gathering information to comprehend the intricacies of this emerging technology and its implications, for workers health.

1. INTRODUCTION

The rise of 3D printing technology also known as manufacturing is a milestone, in the development of modern production methods. This versatile technology has made its way into industries like medicine, engineering, fashion and manufacturing. It has revolutionized approaches by enabling the creation of structures, rapid prototyping and cost effectiveness. In the field 3D printing has played a role in preoperative planning, medical education and the production of personalized medical devices. It has also had an impact on manufacturing by contributing to equipment production, material research and software design. However, it's important to acknowledge that there are challenges associated with 3D printing technology. One major concern is the health effects caused by emissions from these printers. These emissions include particulate matter, compounds (VOCs) and ultrafine particles that could potentially pose health risks such as respiratory problems and chemical exposure for those working closely with these printers. Additionally, there are risks related to air quality and waste management that need to be addressed. Given the evolving nature of research, in this field it is crucial to assess and minimize these emissions in order to protect health and reduce environmental impact.

This study aims to fill the knowledge gap and find ways to reduce emissions from 3D printing processes. It involves conducting an assessment of these emissions focusing on types of 3D printers the influence of operating conditions and the effectiveness of different strategies to mitigate them. The research approach combines experiments, empirical analysis and quantitative methods to gain an understanding of printer emissions and their impacts. In controlled laboratory experiments we measure emissions using printers and materials, under operating conditions. Additionally field studies in real world 3D printing environments provide insights into emission dynamics beyond controlled settings. The collected data is then analyzed statistically to identify patterns, relationships between variables and the effects of factors on emission levels. To steer this research in the direction we have established objectives. These include quantifying emissions from 3D printing technologies assessing how operating conditions affect emissions evaluating the effectiveness of mitigation strategies and developing protocols for testing printer emissions. We have also formulated hypotheses to test relationships, between these variables and emission levels. In addition, to examining the reasons behind the respiratory illnesses in construction we will also explore methods to reduce dust and silica dust exposure, on construction sites. Furthermore, we will delve into the advantages of implementing 3D printing technology to minimize dust and silica dust exposure.

2. STUDY BACKGROUND

2.1. 3D printing Technology

The technology of 3D printing also referred to as manufacturing has gained recognition, in various industries due to its versatility and wide range of applications. It has been widely adopted in fields such as medicine, engineering, fashion and manufacturing. This is primarily because it allows for the creation of structures, quick prototyping and cost effectiveness (Deng et al., 2019; Wang et al., 2020; Singhvi et al., 2018). In the Medical sector specifically 3D printing has played a role in preoperative planning, medical education and the development of custom-made medical devices (Bangeas et al., 2019; Youssef et al., 2015; Dombroski et al., 2014). Additionally, this technology has found utility in fashion design, furniture manufacturing and the production of precision thin wall castings. Its impact is also visible in pharmaceuticals where it offers approaches to drug delivery systems and tissue engineering (Sun & Zhao, 2017; Shu-guang & Du, 2022; Krutiš et al., 2022). Moreover, intelligent manufacturing greatly benefits from 3D printing as it aids equipment manufacturing processes while facilitating material research and software design (Singhvi et al., 2018). Furthermore, within the fashion industry itself there is growing exploration into using 3D printing for purposes along, with streamlining supply chains through sustainable additive manufacturing practices (Tang & Chen, 2018). As advancements continue to be made in printing technologys capabilities it holds potential to revolutionize multiple sectors by providing innovative solutions that drive technological progress across various industries (Corral et al., 2017).

2.2. Emissions of 3D printing

It is crucial to evaluate and reduce the emissions from printers since they can have effects, on both health and the environment due to the release of airborne particles and volatile organic compounds. Various studies (Mendes et al., 2017), (Vance et al., 2017), and Yi et al. (2016) have examined these emissions. Emphasized the importance of implementing controls and selecting filament compositions to minimize emissions. Another study Gümperlein et al. (2018) has raised concerns about nanoparticle emissions and their potential harm to health highlighting the need for emission reduction. Furthermore, research conducted by Kreiger & Pearce (2013) has shown that distributed manufacturing with printers can potentially reduce emissions. The work by Lee et al. (2023) and Youn et al. (2019) has focused on evaluating particle emissions and studying how these emitted particles behave when deposited underscoring the necessity, for assessment and control measures. Additionally, studies carried out by Dunn et al. Byrley et al. (2020) and Zhang et al. (2022) have highlighted the risks associated with printer emissions emphasizing the significance of strategies aimed at reducing these emissions. Collectively these findings stress the importance of evaluating and mitigating printer emissions in order to protect human health and minimize environmental impact.

2.3. Types of Emissions

Emissions coming from printers include pollutants, like particulate matter volatile organic compounds

(VOCs) and ultrafine particles. These emissions have sparked concerns about their impacts on health and the environment. Research conducted by (Gu et al., 2019), (Lee et al., 2023), and Khaki et al. (2022) has examined these emissions specifically focusing on particulate matter and VOCs released during the printing process. Another study by Jeon et al. (2019) explored how nozzle temperature affects the emission rate of particles when using a printer. Furthermore, studies conducted by Zhang et al. (2022) and Väisänen et al. (2021) have analyzed the emission profiles of VOCs and ultrafine particulate matter emphasizing the need for an assessment and implementation of control measures. The importance of monitoring emissions, from printers has been highlighted by (Peterson et al., 2022) who characterized particle emissions in an office setting. Collectively these studies underscore the significance of evaluating and mitigating emissions from printers to protect health and minimize environmental impact.

2.4. Health and Environmental Concerns

The emissions produced by 3D printers raise concerns, for both health and the environment. This is due to the release of particulate matter compounds (VOCs) and ultrafine particles. Studies conducted by experts in the field such as (Grahame & Schlesinger, 2007), (Zontek et al., 2017), and Bharti & Singh (2017) have emphasized the need to regulate types of particles or sources well as highlighted the ongoing research on the potential health impacts and indoor air quality issues associated with 3D printing emissions. Furthermore, researchers like Krechmer et al. (2021) and Youn et al. (2019) have evaluated the characteristics of nanoparticle formation. Identified air pollutants emitted during 3D printing operations further emphasizing the potential risks to human health from exposure to these emissions. Moreover, studies such as Mohammadian & Nasirzadeh (2021) and Min et al. (2021) have expressed concerns about exposure risks, within 3D printing industries and the emerging health hazards associated with particle and VOC emission. Collectively these studies emphasize the importance of assessing and reducing emissions from printers in order to protect health and minimize environmental harm.

2.5. Sources of Emissions in 3D Printing

The emissions generated by 3D printers come from sources, including the printing process itself the materials used for printing and the components of the printer. Studies conducted by (Gu et al., 2019), (Mendes et al., 2017), and Vance et al. (2017) have examined these emissions. Pointed out the existence of particulate matter and volatile organic compounds (VOCs) during printing activities. The act of printing which involves heating and extruding filament materials has been identified as a source of emissions as shown by Lee et al. (2023) and (Gümperlein et al., 2018). Additionally, research has indicated that the chemical composition of filament materials and the temperature of the printer nozzle can affect emission rates as indicated by Chýlek et al. (2021) and (Khaki et al., 2021). Furthermore, components such, as the nozzle and enclosure have also been found to contribute to emissions highlighted by Khaki et al. (2021) and (Ciklacandir et al., 2022). The importance of assessing and mitigating emissions from printers to protect health and minimize environmental impact has been emphasized in studies conducted by Min et al. (2021) and (Dunn et al., 2020) as well. Collectively these findings underscore the significance of implementing targeted prevention strategies and control measures concerning these emissions from 3D printers. The emission characteristics differ among types of printers due to factors like printing processes employed materials used for printing and printer components. Research studies carried out by by (Gu et al., 2019), (Mendes et al., 2017), and Yi et al. (2016) have provided insights into these emissions while highlighting their presence during printing operations, in terms of particulate matter and volatile organic compounds.

The emission characteristics of printers are influenced by the type of filament materials used, as shown in studies conducted by Khaki et al. (2021) and (Dunn et al., 2020). It has also been found that components, like the nozzle and enclosure of the printer contribute to emissions as highlighted by Zhang et al. (2022) and (Byrley et al., 2020). These research findings emphasize the importance of evaluating and mitigating emissions from printers to protect health and minimize environmental impact. The different emission profiles observed in 3D printers highlight the need, for assessment and control measures to address potential health risks and environmental concerns associated with 3D printing emissions.

2.6. Health and Environmental Impact of the 3D Printing Emissions

Exposure, to emissions from printers can potentially impact the health of individuals working with or near these printers. Studies conducted by experts in the field like (Zhang, 2017), (Mendes et al., 2017), and Vance et al. (2017) have shed light on the risks associated with air quality, specifically related to particulate emissions. These emissions have been found to release particles and volatile organic compounds, which can pose health hazards. The research of Yi et al. (2016) and (Oskui et al., 2015) also indicates that exposure to printer emissions may be linked to conditions such as asthma and allergic rhinitis. Another study of (Youn et al., 2019)focused on evaluating nanoparticle formation and hazardous air pollutants emitted during printing operations highlighting the importance of assessing and minimizing these risks for well being. It is crucial to prioritize the evaluation and mitigation of emissions, from printers in order to protect health from potential hazards associated with exposure.

The increasing worry, over the consequences of emissions from 3D printers mainly revolves around air quality and waste management. Research conducted by experts such as (Azimi et al., 2016), (Vance et al., 2017), and Khaki et al. (2022) has shed light on the effects of printer emissions on indoor air quality emphasizing the importance of being cautious when operating printers in poorly ventilated spaces. The release of particles and volatile organic compounds (VOCs) from printers has been linked to possible health hazards as indicated by Zhang et al. (2022) and (Peterson et al., 2022). Additionally concerns about the impact of 3D printing have been raised in studies conducted by Kreiger & Pearce (2013) and Khaki et al. (2022) which provide guidelines for improving air quality and reducing particulate matter emissions. These collective findings underscore the significance of assessing and mitigating emissions from printers to protect health and minimize environmental damage particularly with regard, to air quality and waste management.

2.7. 3D printing emissions Assessment techniques

Various methods and approaches are used to evaluate the emissions of printers including air sampling, particle characterization and gas analysis. Researchers like (Azimi et al., 2016), (Vance et al., 2017), and Stabile et al. (2016) have used air sampling techniques to measure the emitted particles and gases, from 3D printers providing information about their composition and concentration. By studying particle characterization methods as demonstrated by Lee et al. (2023) and (Yi et al., 2016)scientists can assess the size distribution and number concentration of the particles emitted by 3D printers gaining an understanding of their emissions. Gas analysis techniques, similar to those employed by Byrley et al. (2020) and (Zhang et al., 2022)help determine the presence and concentration of compounds (VOCs) in 3D printer emissions giving insights into potential chemical exposure risks. These combined methodologies offer an approach to evaluate and understand the implications and possible health risks associated with exposure, to 3D printer emissions.

2.8. Mitigation Strategies for 3D Printing Emissions Reduction

In order to decrease the amount of emissions produced by 3D printers there have been suggestions and techniques mentioned in research papers. These include using materials, with emission levels improving ventilation and implementing filtration systems. Studies have examined the emissions produced by 3D printers when using polymers like acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) (Mendes et al., 2017). It has been demonstrated that desktop 3D printers release levels of particles (UFP) and volatile organic compounds (VOCs) (Yi et al., 2016). To tackle this issue accessories like high efficiency particulate air (HEPA) filter attachments have been designed to reduce emissions from enclosed printers (Katz et al., 2019). Additionally it has been discovered that using enclosures with airtightness can effectively limit nanoparticle emissions (Viitanen et al., 2021). Moreover research has shown that adding cost controls to existing 3D printers can significantly minimize emissions in work environments (Dunn et al., 2020). It has also been highlighted that our knowledge regarding the emission safety of used 3D printers is limited emphasizing the need for investigation in this field (Stańczak et al., 2021). Overall the literature emphasizes how crucial it is to manage emissions and exposure from combinations of 3D printer models and filaments particularly, in indoor settings in order to minimize potential health risks (Azimi et al., 2017).

The adoption of measures to reduce emissions, in 3D printing settings has gained support from real life instances and research studies. For example one study examined the emission characteristics of substances during the process known as fused deposition modeling in printing highlighting the importance of understanding and controlling emissions from such processes (Kim et al., 2015). Another comprehensive review explored endeavors that utilized 3D printing technologies for manufacturing dosage forms highlighting both the opportunities and challenges in this field (Alhnan et al., 2016). Additionally a study investigated the emissions of submicrometer aerosols from printers in controlled environments while also assessing exposure to these aerosols under real world conditions across different indoor settings. This research shed light on the significance of comprehending emission dynamics within contexts. These instances underscore both the importance of implementing emission reduction strategies and the need for research and best practices, within 3D printing environments.

Ongoing studies and research, in reducing emissions from printers have attracted attention in recent literature. These studies have highlighted the release of particles (UFPs) and harmful volatile organic compounds (VOCs) from 3D printers emphasizing the importance of understanding and controlling these emissions Azimi et al. (2016). Research has also suggested implementing control methods, such as using harmful materials preventing contaminants from being released and employing filters or adsorbents to minimize emissions during 3D printing processes (Kim et al., 2015). Moreover, investigations have been conducted to assess the emission rates of particles produced by desktop 3D printers using thermoplastic materials in various environments like offices and clean rooms (Zhou et al., 2015). This research provides insights into how 3D printing can impact indoor air quality (Hájková, 2023). Additionally, there has been exploration into improving materials for 3D printing specifically focusing on optimizing setting times and enhancing properties through the development of materials (Youn et al., 2019). Furthermore studies have evaluated the formation of nanoparticles and hazardous air pollutants emitted during printing operations shedding light on how these emissions behave within the respiratory system. All these ongoing research efforts highlight that addressing emission reduction, in printing requires an approach encompassing materials, technology and regulations.

2.9. Problem Statement and Research Gap

The widespread use of printing technology also known as manufacturing in various industries such, as medicine, engineering, fashion and manufacturing emphasizes its importance in modern production processes. This technology is renowned for its ability to create structures quickly and cost effectively which has transformed manufacturing methods. However as these advancements occur significant concerns have arisen regarding the health impacts caused by emissions from printers. These emissions include pollutants like particulate matter compounds (VOCs) and ultrafine particles. They pose health risks not to individuals working near these printers but also to the broader environment. Research indicates that the emissions from printers can lead to issues, chemical exposure and other health problems. Additionally the environmental effects of these emissions concerning air quality and waste management are becoming increasingly worrisome. Despite the progress made in printing technology there is still a need for comprehensive assessments and effective mitigation strategies for these emissions. The existing body of research on this topic is extensive. Often lacks testing and evaluation protocols. Consequently, there is inconsistency, in findings and uncertainty surrounding mitigation approaches.

Moreover, there is a pressing need, for conducting investigations into the emission patterns exhibited by various types of 3D printers. These emission profiles are influenced by factors such as the printing technique employed the materials used for filament and the components of the printer itself. While existing literature on printer emissions primarily focuses on characterizing these emissions and their potential impacts on health and the environment there is a shortage of studies that combine emission assessment with the development and implementation of effective strategies to mitigate these emissions. Specifically, it is crucial to conduct research in testing protocols to enhance reliability and comparability when evaluating emissions in settings and using various methodologies. Furthermore, although some strategies have been proposed to mitigate emissions from printers, such as utilizing low emission materials or improving ventilation systems there exists a gap in research concerning their effectiveness and feasibility within printing environments. This includes gaining an understanding of how emissions behave in real world scenarios and devising tailored solutions that target sources and types of emissions. Therefore, as 3D printing technology continues to advance across sectors it becomes paramount to address these gaps through research. Doing so will enable us to harness the benefits offered by this technology while minimizing its potential risks, to human health and negative environmental impacts.

3. EMPIRICAL ANALYSIS

3.1. Utilizing 3D Printing to Enhance Health and Safety Measures at Construction Sites

As per Schuldt et al. (2021), Construction 3D printing, which is also referred to as manufacturing involves the process of joining materials layer by layer. Similar, to Fused Deposition Modeling 3D printers this technique utilizes extrusion technology. The process begins with creating a model using software and then converting it into G code, a language that the printer can understand. (Dávila et al. 2022). Once calibrated, the printer uses the G-code to direct the extrusion of concrete through a nozzle, depositing material in predetermined layers according to the specified model thickness (Pacewicz et al. 2018). Figure 1 provides an illustration of the construction 3D printing process.

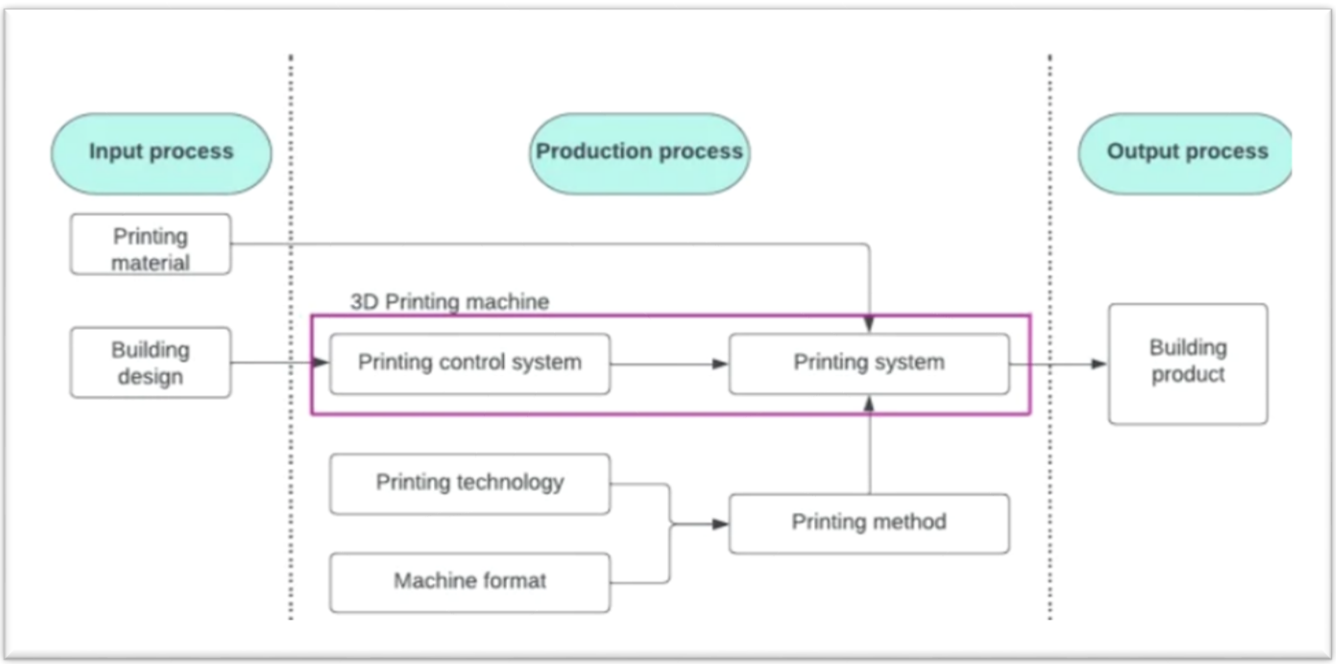

Figure (1) Construction 3D printing process – reproduced from Pan et al. (2021)

Stereolithography, patented by Chuck Hull in 1986 (Pacewicz et al., 2018), is a pivotal 3D printing technology. It employs various materials, predominantly cementitious like concrete, along with cement-based mortar, gypsum-based mortar, aggregates, cement, and additives such as ground granulated blast-furnace slag, fly ash, silica fume, and rock powders (e.g., limestone and quartz powders), altering material properties (Pacewicz et al., 2018). Additionally, metals have found applicability (Sati et al., 2021), while ongoing developments introduce new materials like wood-based and eco-friendly options (Kidwell, 2017). Research investments aimed at enhancing materials could potentially revolutionize the construction industry.

Diverse technologies are employed in 3D printing (Pessoa et al., 2021). These include Binder Jetting (using powdered materials), Directed Energy Deposition (commonly with metal powder and wire feedstock), Material Extrusion (employing thermoplastic filaments and flowable slurries), Material Jetting (utilizing materials such as waxes), Powder Bed Fusion (using powdered materials), Sheet Lamination (involving paper, polymer, and metal sheets), and Vat Photopolymerization (employing materials like polymer resins). In the domain of cementitious materials, five common methods are employed: Contour Crafting, Concrete Printing, D-shape, Fused Deposition Modeling (FDM), and Fused Material Powder (Sati et al., 2021).

According to Pessoa et al. (2021), Contour Crafting is widely considered the technique, for 3D printing, in the Architecture, Engineering and Construction industry. This perspective is backed by Ghaffar et al. (2018).

The existing body of research, on 3D printing in construction primarily focuses on the technologies used materials involved and the potential effects on the job market if it becomes widely adopted. However there is a lack of information, about how it affects the health and safety of workers. Since there have been a few completed projects using this technology further studies are needed to understand its implications.

3.2. Findings from Literature Review

The research review identified strategies, for managing dust exposure, which include using water spraying (Shi et al., 2023), respiratory protective equipment like masks and filters well as dust removal systems such as dry vacuums and local exhaust ventilation (Hilti, 2019). In addition newer approaches involve dust fixing methods through fastening of drilling and the use of wearable technology to monitor dust exposure (Hilti, 2019). While water application and respiratory protective equipment are established and cost effective ways to manage dust exposure challenges arise when workers choose not to use the provided measures due to factors, like discomfort, inadequate training or lack of supervision.

3.3. Findings from Questionnaire

To discover methods, for minimizing dust and silica exposure the survey delved into approaches. Results indicated that 95% of participants leaned towards relying on respiratory protective gear and dust removal systems like vacuums, deeming them quite crucial or very important. However, the trust percentage slightly dropped for methods like water spraying (71% of respondents) and dust-free fixing via fastening instead of drilling (68% of respondents). Figure 2 encapsulates these findings from the online survey, spotlighting the strategies perceived as very important or quite important by respondents aiming to minimize on-site dust and silica dust exposure.

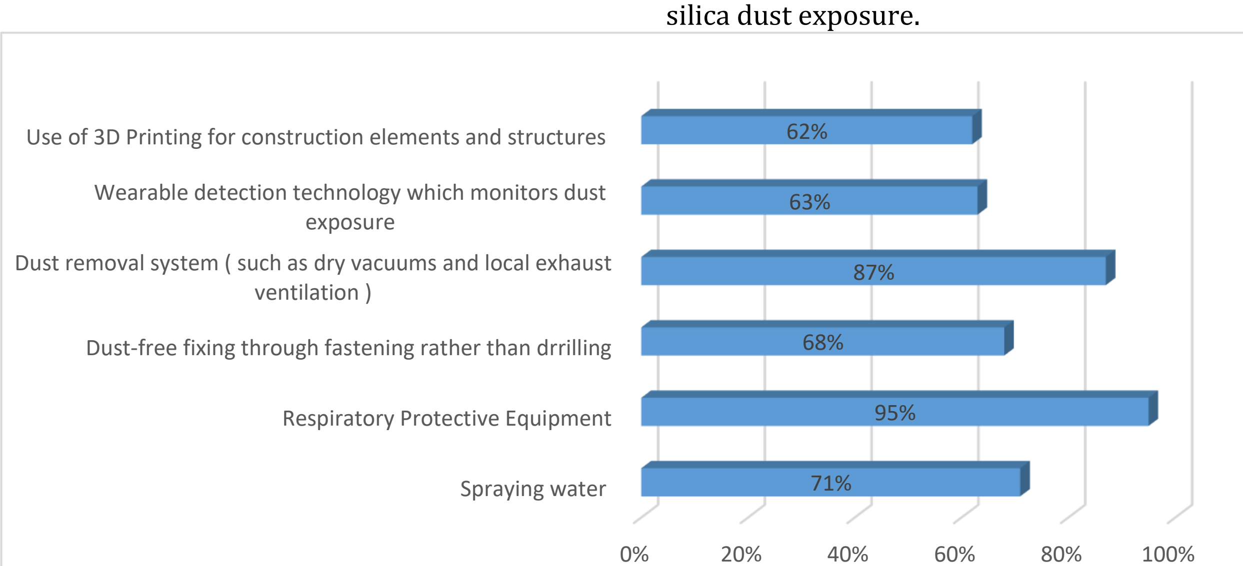

Figure 2. Strategies to minimize onsite dust/silica dust exposure

3.4. Findings from Interviews

Insights gathered from the interviews highlighted several primary strategies: water spraying, the use of respiratory protective equipment (RPE), exhaust ventilation, wet grinding practices, closed mixer systems, 3D printing, prefabrication methods, administrative controls, and periodic medical testing. This synthesis is depicted in Figure 3.

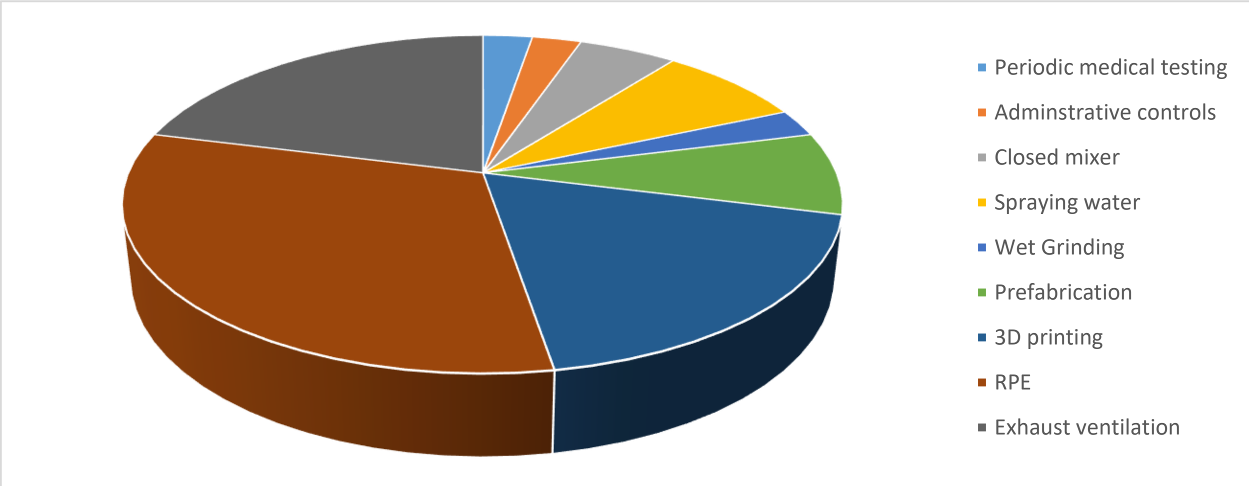

Figure 3. The most important measures in managing onsite dust/ silica dust exposure.

4. CONCLUSION

To meet the research goals, a mixed research approach was employed, combining secondary and primary data collection methods. Existing literature was reviewed extensively to grasp the nuances of the new technology. Furthermore, an online questionnaire survey and a series of interviews were conducted, drawing valuable insights from the firsthand experiences of interviewees. These research methods successfully fulfilled the established objectives, encompassing the identification of prevalent respiratory diseases in construction, strategies for minimizing on-site dust/silica exposure, benefits of 3D printing in reducing on-site dust/silica exposure, barriers to implementing 3D printing for dust reduction, and strategies to promote wider adoption of construction 3D printing to reduce long-term respiratory issues among workers.

This study encouraged participants to envision the potential of this innovative technology, emphasizing its benefits not only in sustainability but also in health. Due to the novelty of the technology, this study might not present definitive results but rather prompt further exploration as the technology progresses. By shedding light on different perspectives, this study underscores the potential of this new technology while considering ways to navigate its associated challenges.

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