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Exceedance of environmental exposure limits to crystalline silica in communities surrounding gold mine tailings storage facilities in South Africa

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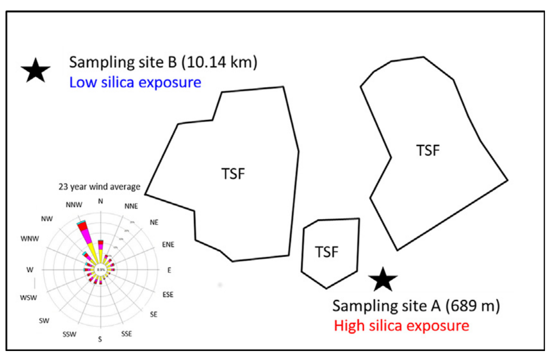
HIGHLIGHTS

- This study assessed the need for non-occupational silica limits for South Africa.
- PM_{10} and PM_4 silica levels exceeded the international interim limits.
- Populations nearby mine tailings may be at risk to develop adverse health effects.
- This study confirms unacceptably high non-occupational silica exposures.
- South Africa needs to enforce a non-occupational silica limit.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Unlike occupational silica exposures, the association between non-occupational silica exposures and adverse health effects is not well researched, despite its occurrence in communities close to dust-generating sources such as tailings storage facilities (TSFs). Recent studies have shown that communities surrounding TSFs in South Africa often complain about the onset of dust-related health effects. Even though international interim non-occupational crystalline silica limits have been established, South Africa is yet to enforce its own limits for residential areas close to TSF sites.
Objective: The objective of the study was to assess the need to enforce non-occupational crystalline silica limits for South Africa.
Methods: The methods involved (1) Quantifying the silica polymorph content in bulk dust collected from TSFs in South Africa; (2) Assessing the possibility of the dust to reach surrounding communities through ambient and personal filter sampling and; (3) Conducting risk characterisation for both cancer and non-cancer endpoints.
Results: All bulk dust samples consisted mostly of crystalline silica (73.14–87.09%). Large percentages of nanoparticles were identified in all bulk samples (66.8–70.7%) indicating the possibility of the dust to lodge deep within the lungs. The crystalline silica levels obtained from ambient PM_{10} sampling and personal PM_4 sampling all exceeded the international crystalline silica interim limits and reached maximum levels of 90 and 50.9 $\mu g \cdot m^{-3}$, respectively. For three TSFs, sampling sites close to the TSFs showed higher PM_4 silica levels compared to sites further from TSFs. Risk characterisation revealed the possibility of cancer and non-cancer health effects when chronically exposed to silica levels recorded during the study.

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Conclusion: The results indicate unacceptable crystalline silica exposures in surrounding communities and the need for enforcement of an ambient silica limit for South Africa.

1. Introduction

Silica or silicon dioxide (SiO_2) exists in both crystalline and amorphous forms. Crystalline silica, which occurs in different polymorphic forms such as quartz, cristoballite and tridymite (NIOSH, 1994), has been classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen (IARC, 2009), based on the fact that chronic occupational exposure to high levels of crystalline silica dust for prolonged periods may produce carcinogenic adverse health effects such as lung cancer (Vida et al., 2010). Chronic occupational exposure to crystalline silica may also produce non-malignant adverse health effects such as pulmonary silicosis (Craighead, 1988), chronic obstructive pulmonary disease, chronic bronchitis, emphysema, small airways disease (Hnizdo and Vallyathan, 2003), tuberculosis/silicotuberculosis (Milovanović et al., 2011), autoimmune diseases (rheumatoid arthritis, scleroderma, systemic lupus erythematosus) (Steenland and Goldsmith, 1995) and kidney disease (Vupputuri et al., 2012), while acute occupational exposures to high concentrations of crystalline silica have shown to cause cough, shortness of breath and pulmonary alveolar lipoproteinosis (acute silicosis) (Chapman, 1932). Several reviews addressing these adverse health effects of occupational crystalline silica exposure have previously been published (Beckett, 1997; Greenberg et al., 2007).

Non-occupational exposures to crystalline silica are also possible, particularly in communities near silica-dust generating sources. However, unlike occupational crystalline silica exposures, non-occupational exposures are rarely assessed and little information is currently available. A few studies have assessed the non-occupational concentration of crystalline silica in both PM_{10} and respirable PM_4 fractions. For example, it was found that the 24 h non-occupational (or ambient) PM_{10} crystalline silica levels at sites nearby a silica-rich slate pencil industry were 41.07–57.22 $\mu g \cdot m^{-3}$, compared to 3.51 $\mu g \cdot m^{-3}$ at control sites > 5 km away (Bhagia, 2009), indicating possible silica exposure to surrounding communities. On the other hand, Richards and Brozell (2015), found that the 24 h ambient PM_4 crystalline silica levels from the fence lines of three frac sand mines and one frac sand processing plant in Wisconsin were comparable to background silica levels, indicating a lack of exposure to surrounding communities. In other studies, non-occupational pneumoconiosis was identified in regions where the crystalline silica content of soil is high and dust storms common (Norboo et al., 1991; Saiyed et al., 1991). A few other studies addressing non-occupational silica exposures are discussed in the review by Bhagia (2012).

In the absence of an established ambient, chronic crystalline silica limit, several interim limits have been set by various international institutions and state agencies. These interim limits, however, are not based on quantitative risk assessments and are calculated through the derivation of a point of departure (POD) value (e.g. benchmark dose/concentration (BMD/C), lowest observed adverse effect level (LOAEL) or no observed adverse effect level (NOAEL)) using the epidemiological data from miners exposed to silica. An uncertainty factor is then applied to the POD to account for the general population including sensitive groups such as children and the elderly. For example, using the epidemiological data from white South African miners (Hnizdo and Sluis-Cremer, 1993), the California Office of Environmental Health Hazard Assessment (OEHHA) used benchmark dose modelling to derive a BMC, which was time-adjusted from workplace exposure to an equivalent continuous environmental exposure. The final, time-adjusted BMC value of 9.8 $\mu g \cdot m^{-3}$ was divided by an uncertainty factor of 3 (i.e. accounting for the general population), leading to a reference interim silica limit of 3 $\mu g \cdot m^{-3}$ (OEHHA, 2005; Collins et al., 2005). Epidemiological data from other supportive mining studies (Chen et al., 2001; Churchyard et al., 2004; Hughes et al., 1998; Steenland and Brown, 1995) were also used by the OEHHA to calculate reference interim silica limits, which ranged from 3 to 6 $\mu g \cdot m^{-3}$. Based on these results the OEHHA settled on a reference interim silica limit of 3 $\mu g \cdot m^{-3}$, specifically for the respirable PM_4 fraction (OEHHA, 2005; Collins et al., 2005). Using a similar approach, the state of Vermont and the United States Environmental Protection Agency (US EPA) have set their silica limits for the PM_{10} fraction at 0.12 $\mu g \cdot m^{-3}$ (Agency of Natural Resources, 1998) and 5 $\mu g \cdot m^{-3}$ (US EPA, 1996), respectively.

Even though an interim ambient silica limit of 3 $\mu g \cdot m^{-3}$ was calculated by OEHHA using a South African epidemiological study, this limit has not yet been recognised, enforced or monitored in residential areas by South African governmental agencies, despite the presence of silica-rich dust generating sources such as gold tailings storage facilities (TSFs; mine waste dumps). TSFs are a result of Johannesburg's rich gold mining history (Nelson, 2013) and >270 TSFs are currently visible on the South African landscape, covering a total area of 180 km^2 (Rösner, 2001). Due to the rapid expansion of urbanised areas, exposure of surrounding communities to silica-rich dust emitted from these TSFs, during windy periods, is to be expected. Indeed, Kneen et al., 2015) showed that, due to a rapid growth of residential areas, surrounding communities around three major gold mine TSFs located in the Witwatersrand goldfield in Johannesburg, Gauteng, South Africa, showed substantial encroachment onto TSF territory from the period of 1952 to 2011. Some human residences are known to be even as close as 100 m from these TSFs (Rossouw et al., 2009). The main reason for this encroachment is due to a total disregard by local governments of the buffer zone guidelines defined by the Gauteng Department of Agriculture Conservation and Environment (GDACE) as being at least 500–1000 m between the foot of the TSF and the nearest development (GDACE, 2009). As a result, recent reports of discontented community members complaining about the onset of possible dust-related respiratory illnesses have been recorded (Wright et al., 2014; Oguntoke and Annegarn, 2014).

The objectives of the current study were therefore to determine whether dust generated from TSFs did indeed contain any of the crystalline silica polymorphs and also whether the dust could reach surrounding communities. Our study sites included four TSFs located in the Witwatersrand goldfield and one TSF located in the Klerksdorp goldfield in the North-West province. The content of silica polymorphs in bulk dust collected from these TSFs as well as in ambient PM_{10} and in personal PM_4 fractions was assessed. Since crystalline silica is associated with both cancer and non-cancer adverse health effects, the study also sought to conduct a risk characterisation for both these end-points in the communities surrounding the TSFs and to assess the possible need for a non-occupational interim silica limit, specifically for South Africa.

2. Methods

2.1. TSFs

Fig. 1 shows the locations of the five TSFs studied in South Africa; four TSFs located in Witwatersrand, Johannesburg, Gauteng (hereafter referred to as TSFs 1–4) and one TSF located in Klerksdorp, North-West (hereafter referred to as TSF 5). The names of the TSFs have deliberately been omitted from this manuscript to protect the identities of the affiliated mining companies. These TSFs were chosen based on either one or more of the following criteria: (1) High population densities