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SHORT COMMUNICATION

Alternative construction materials from industrial side streams: Are they safe?

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Abstract The global population is continually generating vast amounts of waste materials across various sectors, leading to environmental challenges associated with landfill disposal. This study aims to examine the leachate and the antimicrobial properties of several waste materials to explore their potential applicability in the construction industry. Here, ICP-OES analysis and Kirby Bauer test were conducted on ready-mix concrete plant (powder residues), precast industries, recycled alkali-activated materials, municipal solid waste incinerated (MSWI) bottom ash, MSWI fly ash, High alumina tailing, and High magnesia tailing, to explore their potential applicability in the construction industry. Aluminium, calcium, silicon, potassium, and magnesium were the major ions leached from the waste materials, with MSWI fly ash and bottom ash showing higher levels of heavy metal leaching. The levels of leached aluminium, barium, chromium, lead, and zinc from MSWI fly ash and bottom ash were quantified, with values reaching up to 28.7 ppm, 4 ppm, 3.9 ppm, 11 ppm, and 25 ppm, respectively. Additionally, all samples demonstrated some level of antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus,* which could be related to their alkaline pH and the release of certain ions. Improper disposal of waste materials in an open environment can potentially lead to contamination by heavy metals and harmful bacteria, which can pose a significant health risk during handling. This study results provided valuable information regarding the safety of using these wastes in the construction industry.

Keywords Antimicrobial properties · Heavy metal · Leaching · MSWI · Tailings

1 Introduction

The global population is currently expanding by approximately 1% every year, resulting in an increase of roughly 80 million people annually (Najafi and Khanbilvardi 2019). It is projected to hit 9.8 billion in the global population by 2050, necessitating a higher rate of construction, development of infrastructure, demand for food, energy, and many more things to meet the growing demand. The growing industrialization, urbanization, and population also lead to the generation of enormous waste materials in various sectors that will have severe environmental consequences. Commonly, most of the waste materials end up in landfills, and if some of the waste materials contain toxic and heavy metals, that might further damage the purity of groundwater (Smołka-Danielowska 2006).

The solid ashes from MSW (municipal solid waste) incineration can be classified into fly ash (FA) and bottom ash (BA) (Tang et al. 2015). FA consists of fine particles captured by the flue gas dust removal device and represents around 3–5% of the initial MSW (Yang et al. 2012; Zhu et al. 2020). On the other hand, BA is a heterogeneous solid granule composed of various components like ceramics, cullet, minerals, slag/molten phase, metal oxides, and unburnt substances, with a wide range of particle sizes (Li et al. 2022). Literaturestudies reported that MSWI ashes commonly contain heavy metals such as Cr, Cu, Cd, Hg, Ni, Pb, and Zn (Tang et al. 2015; Yin et al. 2018). In several countries, fly ash is categorized as hazardous waste, necessitating stabilization/solidification treatments prior to

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landfill disposal (Blasenbauer et al. 2020). On the other hands, mine tailings are considered as a major source of heavy metal pollution in many countries (Bhattacharya et al. 2006; Varrica et al. 2014; Wang et al. 2019). Over the past few years, numerous studies have reported the potential escalation of heavy metal levels in agricultural soils, sediments, groundwater, surface water, and surrounding plants near abandoned mine tailings (Boularbah et al. 2005; Larios et al. 2013; Sun et al. 2018). Mine tailings piled in the open air without environmental mitigation measures may leach heavy metals with precipitation, leading to long-term heavy metal release into the environment and causing harm the environment (Jiang et al. 2021b). Literature studies evidently show the presence of As, Cd, Cu, Pb, and Zn in different mine tailings (Cheong et al. 2011; Khorasanipour et al. 2011; Khoeurn et al. 2019). Similarly, numerous researchers have reported the leaching of heavy metals from recycled concrete (Spanka and Schneider 2015; Sanger et al. 2019). It is well-documented that exposure to heavy metals can lead to severe health issues in both humans and other animals (Reis et al. 2010; Mandal 2017; Nyambura et al. 2020). Heavy metals leached from tailings, MSWI, and other contaminated waste can contaminate surrounding soil, and vegetable plants in that area may then absorb these metals (Wang et al. 2005; Lai et al. 2010). Chronic intake of such contaminated vegetables could severely harm humans and animals, leading to health issues like cancer, liver problems, and neurological disorders (Liu et al. 2013). Therefore, it is essential to assess the presence of heavy metals in MSWI residues, tailings, and construction waste before their utilization in construction or other applications.

Furthermore, the long-term disposal of waste in open-air environments can lead to bacterial contamination posing health risks during handling. A recent study conducted by (Bis et al. 2013) and (Przybulewska et al. 2010) reported that the direct disposal of MSW in open air could result in microbiological contamination, including fungi, viruses, and bacteria. (Kiledal et al. 2021) reported that concrete weathered for several years might accumulate bacteria. During the casting process, the pH of concrete is likely to be $\sim$12.5, and this highly alkaline environment poses metabolic and physical challenges to the microbes inhabiting it (Horikoshi 1999). It was also reported that the waste materials containing heavy metals have a detrimental impact on the survival, growth, diversity and ecological functions of microbial communities (Turpeinen et al. 2004; Jiang et al. 2021a). Literature studies suggest that there have been limited studies conducted on the antibacterial properties of construction materials. The bacterial accumulation in construction waste, mine tailings, and MSWI disposed of over extended periods needs to be investigated to ensure the safety of workers during handling and utilization.

Literature studies suggest the use of waste materials, including MSWI ashes, tailings, and construction and demolition waste for their application as construction materials (Perumal et al. 2020; Moukannaa et al. 2022; Kursula et al. 2022). (Liu et al. 2022) reported leaching of Cu, Cr, Pb, As, Ni from MSWI fly ash obtained from Beijing, China. Literature studies also indicate that the chemical composition of MSWI may vary depending on geographical location, season, and local habits (Dou et al. 2017). For example, during summer, the increased use of aluminium foils could raise the metallic aluminium content in MSWI. In this context, studying the compositional and leaching behaviour of waste materials generated in Finland is essential. Furthermore, there is no published article studying the antibacterial properties of construction waste, MSWI, and tailings. This study aims to fill this gap by comparing the leaching behaviour, and antibacterial properties of various waste materials, including ready-mix concrete (RMC) powder, precast industrial sludge (PIS) and recycled alkali-activated material (RAAM), MSWI bottom ash (MSWI-BA), MSWI fly ash (MSWI-FA), High alumina (HA) tailings, and High magnesia (HM) tailings. The study results indicated that some of the waste materials or by-products may contain heavy metals, emphasizing the need for proper waste management practises to avoid significant environmental impact. The study results also highlight the potential antimicrobial properties of such materials, indicating no health risk for bacterial-related health issues during handling.

2 Materials and methods

2.1 Materials

Seven distinct waste materials, including RMC (Kursula et al. 2022),PIS (Moukannaa et al. 2022), RAAM, MSWI BA, MSWI FA (Perumal and Illikainen 2023), H-AI tailings, and H-Mg tailings (Perumal et al. 2021), were used to study the leaching behaviour and antimicrobial activities. The waste powder of the ready mix was obtained from a local ready-mix plant. RAAM and PIS were taken from a local area of the University of Oulu and Jaro Betongsystemer AS (Norway), respectively. All the samples were powdered for leaching and antimicrobial analysis. The oxide composition of the waste materials was analysed using X-ray fluorescence spectroscopy (XRF) and presented in Table 1.

Table 1 Chemical composition of waste and by-product materials from various construction materials, tailings, and MSWI

Materials	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	SO_3	Others
RMC	15.6	1.8	57.5	10.6	2.6	–	–	–	11.9
PIS	24.20	1.5	38.90	7.60	3.70	0.90	1.30	2.2	–
RAAM	13.7	3.1	57.4	3.6	0.4	0.6	2.7	1.3	16.7
MSWI BA	18.20	2.10	38.50	10.60	11.90	–	–	2.70	16
MSWI FA	26.70	3.10	26.60	9.10	2.9	–	–	7.5	24.1
HA tailings	16.5	4.9	45.8	22.1	8.6	0.3	1.2	–	–
HM tailings	12.8	22.9	47.0	2.3	13.3	0.1	0.4	0.3	–

2.2 Methods

2.2.1 *Leaching test*

The leaching of heavy metals from the samples was conducted according to the EN 12457-2:2004 standard. All the samples were crushed to ensure that their size was less than 2 mm. The samples were then mixed with distilled water in a liquid/solid weight ratio of 10 L/kg and kept on a shaking table for 24 h. The leachate solutions were then filtered ($d < 0.45$ µm) and the recovered solutions were acidified to pH 2 using a 69% HNO_3 solution. BS EN ISO 11885:2009 standard was considered for the determination of heavy metals. All the concentrations of ionic metals are reported in units of parts per million (ppm). The detection limit (LOD) for all the ionic metals is 0.1 ppm, while the maximum detectable value is 20 ppm (except for Si, which has a maximum detectable value of 10 ppm).

2.2.2 *Antimicrobial analysis*

The antimicrobial properties of the material samples were investigated using the Kirby-Bauer method. For this investigation, two representative bacterial strains, *Escherichia coli (E. coli)* and *Staphylococcus aureus (S. aureus)*, were chosen for the incubation (Blanco et al. 2023). Before the analysis, all the samples were powdered and compressed into small discs of 150 mg and 300 mg, which were then sterilized under UV light for 1 h. TBX Medium and Baird Parker Agar Base were prepared and sterilized at 120 °C for 15 min and slowly cooled before being poured directly into Petri dishes at 50 °C. While, before pouring, BPA was cooled to 50 °C and enriched with egg yolk tellurite emulsion (20%).

The bacterial strains were dissolved in 0.9% NaCl distilled saline water, and suspensions of 10^9 CFU/mL were plated on the respective solid agar media. The sample discs were placed in the middle of Petri dishes before incubation. The bacteria were incubated in Petri plates with 150 and 300 mg sample discs at a controlled temperatures of 44 °C and 36 °C for 24 h for *E. coli*, and *S. aureus*, respectively. The diameters of the inhibition halos (IDs) were measured, and the reduction of bacterial viability was calculated using the equation BV (%) = 100*(PD−IDs)/PD, where PD is the diameter of the Petri dish (6 cm).

3 Results and discussion

3.1 Leaching

The conversion of waste materials into building materials is part of the move from a linear to a circular economy; nevertheless, the usage of such secondary building materials can deteriorate both soil and groundwater quality due to pollutant leaching. Table 2 shows the leaching concentration of ionic metals in different types of waste materials obtained from local areas of Finland. It was observed that Al, B, Ca, Fe, K, Mg, Na, and Si were the major ions released from the waste materials. HA tailings and HM tailings showed comparatively lower Na leaching levels of 8.7 and 16.3 ppm respectively, while other samples had significantly higher levels of Na leaching, ranging from 123 to 2517 ppm. It was observed that the leaching of Na, Ca, Si, K, and Mg from RMC exceeded 0.1 ppm, whereas all other ions remained below 0.1 ppm. Similarly, in precast industrial sludge, Na, Mg, Ca, Si, K, and Al; in recycled alkali-activated material Na, Ca, Al, Mg, K, Si, and B; and in bottom ash, Na, Ca, Al, Mg, K, Si, and B were above 0.1 ppm. Leaching of Al was above 0.1 ppm for all the samples except RMC and HM-Tailings. MSWI-BA and MSWI-FA exhibited a notably higher degree of Al leaching compared to other materials. Nonetheless, except for RMC and HM-Tailings, all samples showed Al leaching above 0.1 ppm. The disposal of aluminium packaging materials as waste contributes to the presence of more aluminium in MSWI-FA and MSWI-BA (Gökelma et al. 2021). It was observed that both MSWI FA and MSWI BA leached a significant number of metals compared to other samples. The evidence of several heavy metals, including AI, As, B, Ba, Cd, Cr, Cu, Fe, Mg, Ni, Pb, and Zn, was found in the incinerated ash, and MSWI FA exhibited a higher concentration of heavy metals than bottom ash. Nonetheless, findings from the study indicate that the

Table 2 Leachate of toxic and heavy metals from the waste and by-product materials from various construction materials, tailings, and MSWI

Ions (ppm)	RMC	PIS	RAAM	MSWI-BA	MSWI-FA	HA-Tailings	HM-Tailings	EU landfill legislation acceptable limit for landfills (EC 2003)		
								Inert waste	Non-hazardous waste	Hazardous waste
Ag	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1			
Al	< 0.1	2.3	4.7	17.3	28.7	1.6	< 0.1			
As	< 0.1	< 0.1	< 0.1	< 0.1	0.011	< 0.1	< 0.1	0.5	2	25
B	< 0.1	< 0.1	< 0.1	0.18	0.41	< 0.1	< 0.1			
Ba	< 0.1	< 0.1	< 0.1	0.62	4	< 0.1	< 0.1	20	100	300
Be	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1			
Ca	110.0	73.5	37.0	428.7	617.8	7.8	11.1			
Cd	< 0.1	< 0.1	< 0.1	0.002	0.0043	< 0.1	< 0.1	0.04	1	5
Co	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1			
Cr	< 0.1	0.11	< 0.1	3.9	0.21	< 0.1	< 0.1	0.5	10	70
Cu	< 0.1	< 0.1	< 0.1	0.56	0.026	< 0.1	< 0.1	2	50	100
Fe	< 0.1	< 0.1	1.3	0.13	< 0.1	0.36	< 0.1			
K	0.73	0.29	0.36	0.37	3.8	< 0.1	< 0.1			
Mg	0.36	0.77	1.94	1.9	1.9	1.5	12.2			
Mn	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1			
Na	134 (o)	123 (o)	351 (o)	538 (o)	2517 (o)	8.7	16.3			
Ni	< 0.1	< 0.1	< 0.1	0.057	< 0.1	< 0.1	< 0.1	0.4	10	40
Pb	< 0.1	< 0.1	< 0.1	< 0.1	11	< 0.1	< 0.1	0.5	10	50
Sb	< 0.1	< 0.1	< 0.1	< 0.1	0.047	< 0.1	< 0.1	0.06	0.7	5
Se	< 0.1	< 0.1	< 0.1	0.04	0.093	< 0.1	< 0.1	0.1	0.5	7
Si	2.52	0.43	10.6	0.25	1.4	< 0.1	0.6			
Ti	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1			
Zn	< 0.1	< 0.1	< 0.1	1	25	< 0.1	< 0.1	0.5	2	25

leaching of heavy metals in MSWI ashes collected from Finland exhibits a lower level of heavy metals leaching in contrast to the findings in existing literature. (Shim et al. 2005) conducted a comparative analysis of heavy metal leaching in MSWI fly and bottom ashes sourced from Japan and Korea. The study revealed that the leaching of Pb from MSWI fly ash was measured 110 mg/l, and 3.4 mg/l while for MSWI bottom ash, the leaching values were 6.3 mg/l and 3.3 mg/l, for samples obtained from Korea and Japan, respectively. The leaching of Al was ranged between 2.4 and 66 mg/l from bottom ash, whereas for fly ash, the leaching value of Al was 0.01 mg/l. Conversely, Finnish MSWI fly ash exhibited an elevated level of aluminium leaching. Similarly, (Jiao et al. 2016) reported the leaching of Cd at concentrations of 57.3 mg/l and 14.90 mg/l, Cu at concentrations of 423.6 mg/l and 1770 mg/l, and Pb at concentrations of 1623 mg/l and 843.6 mg/l from MSWI fly Ash and bottom, respectively (obtained from Japan).

Table 2 also indicates that the leached heavy metals from various construction waste materials remained within the leaching limits specified by EU landfill legislation. Nonetheless, the chemical composition and leaching of heavy metals of construction waste can be influenced by multiple factors. Therefore, it is advisable to conduct the leaching tests before employing them in any applications. Additionally, proper precautions should be taken during handling to avoid any potential health hazards due to the high heavy metal content.

3.2 Antibacterial activity

The capacity of the materials to suppress bacterial growth is a preferable criterion for several applications. In this work, the antibacterial behaviour of the samples was tested using two bacteria: *S. aureus* and *E. coli*. The former is a Gram-positive bacterium with a cocci-shaped that tends to grow in clusters, often described as "grape-like"

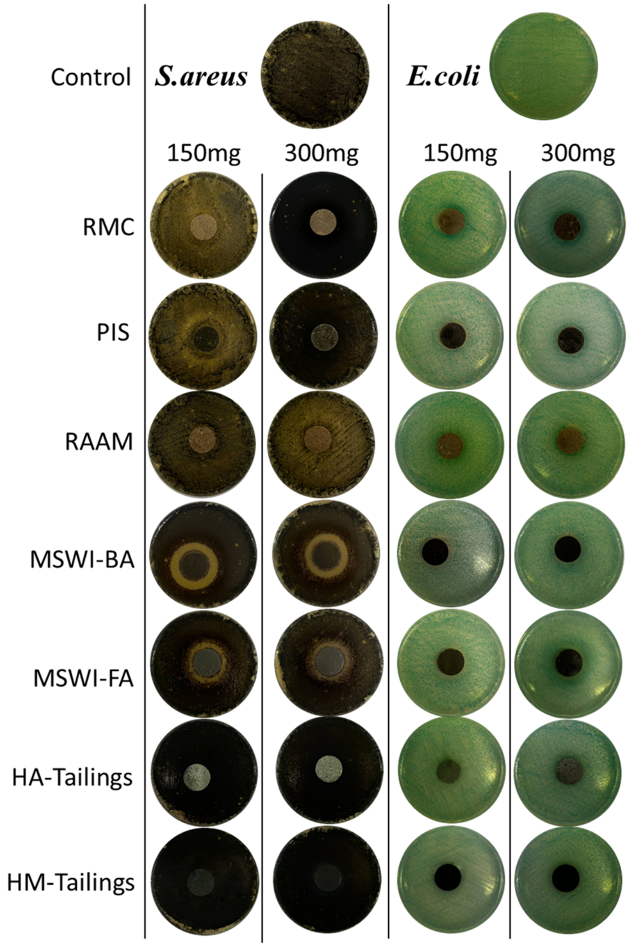

Fig. 1 Tested agar plates samples for the antibacterial analysis

(reference: PMID: 28722898). These organisms, that may develop aerobically or anaerobically, at temperatures ranging from 18 to 40 °C, are the causal agent of several human diseases. Depending on the target of the infection, they are known to induce invasive infections and/or toxin-mediated illnesses (González et al. 2023). The latter is a facultative aerobic-anaerobic Gram-negative rod-shaped bacterium that usually inhabits the lower intestinal tract of warm-blooded animals. Several recent studies have found that some *E. coli* strains can survive and potentially reproduce in extraintestinal environments for extended periods of time, suggesting their possible coexistence with native microbial populations in the environment (Jang et al. 2017). As for *S. aureus* bacterium, also many pathotypes of *E. coli* are known to be responsible for a variety of diseases, including enteric diseases, extraintestinal infections, and meningitis (Kaper et al. 2004). From our results, illustrated in Fig. 1 and Fig. 2, all samples showed antimicrobial activity against both *E. coli* and *S. aureus*. In particular, RMC, RAAM, HA and HM tailings samples had a comparable inhibition power against both *E. coli* and *S. aureus*. Indeed, the Inhibition halo i.e. IDs (Fig. 2A), were 1.30 ± 0.03 cm for all the specimens. The inhibition halos of the PIS (precast industrial sludge) was higher towards *E.coli* (1.42 ± 0.01 cm) rather than *S. aureus* (1.3 ± 0.01 cm). The samples that showed a greater difference in inhibition of *E. Coli* and *S. aureus* were MSWI-BA and MSWI-FA. The former had IDs of 1.6 ± 0.07 cm against *E. coli* and 2.6±0.19 cm against *S. aureus*, whilst the latter had IDs of 1.3 ± 0.01 cm against *E. coli* and 2.3±0.13 cm against *S. aureus*. No dose-dependent behaviour was observed for any of the samples and no significant difference was observed between the weighted amount of analysed samples (150 mg and 300 mg). The results obtained from the observation and measurement of Petri dishes reflect those of bacterial viability. In fact, the lower the antibacterial power of the analysed material, the higher the bacterial vitality score is (Fig. 2B). The antibacterial behaviour of samples could be related to different reasons. First, the nature of the specimens should be considered. Given that our samples have a high alkaline pH, this might prevent the bacteria from growing. Most bacteria live in a pH range between 5 and 8, therefore, bacteria survival outside of this range is difficult, unless the bacteria are basophilic or acidophilic. High pH levels indeed, can cause important changes in cell structure and metabolism which lead to a decrement of bacterial viability (Jin and Kirk 2018). For example, (Padan et al. 2005) reported that when *E. coli* is grown in a medium with a pH of 7.0, the cells have a generation time of 18 min compared to a pH of 8.7, where the cells have a generation time of 25 min. Similar results were achieved by other authors (Parhad and Rao 1974; Padan et al. 2005; Thornton et al. 2018). Similarly, alkaline pH can create hostile growth environments also for *S. aureus* bacteria. Although (Vaish et al. 2019) reported that *S. aureus* has a particular resistance to high pH due to the presence of antiporters on the cell membrane that catalyses the efflux of potentially toxic cytoplasmic cations and keep the intracellular pH homeostasis, (Nostro et al. 2012) stated that higher pH exerted an inhibiting effect on the adhesion of *S. aureus*, which therefore, limits its growth.

The antibacterial activity of samples could also be related to the amount of Na and Ca they release. An excess of ions, such as calcium and sodium, is responsible for causing bacterial death by altering the charge balance of the bacterial cell membrane (Dominguez 2004; Wood 2015). Moreover, calcium is known to act as a second messenger regulating numerous cellular processes. For this reason, the calcium concentration must be finely regulated and both an excess and a deficit of this ion can interfere with cellular processes such as cell adhesion and biofilm formation (King et al. 2020; Catauro et al. 2023). The study findings clearly demonstrate that all the samples exhibit

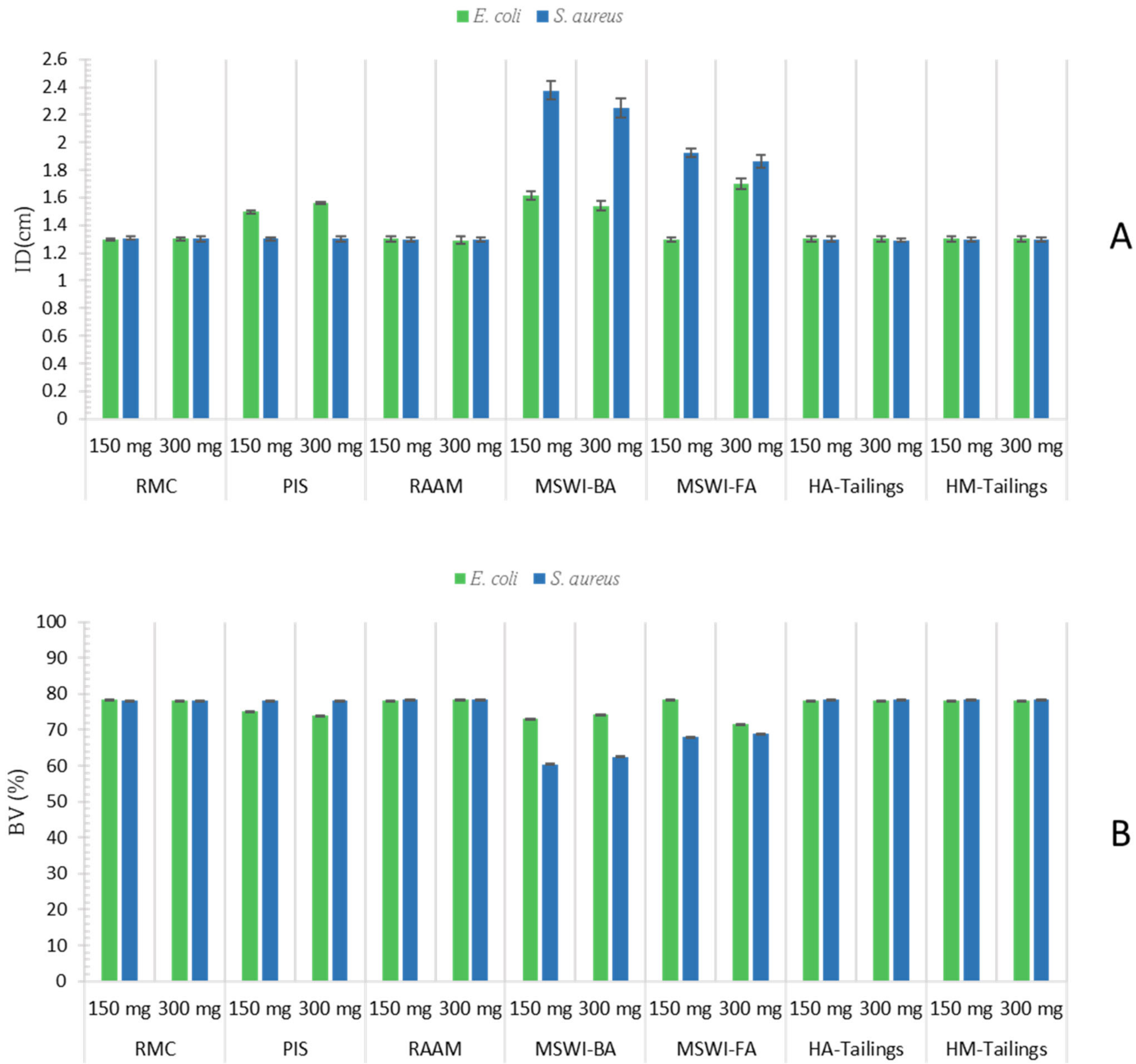

Fig. 2 Inhibition halos Diameter (IDs) (**A**) and Bacterial Viability (**B**) of assayed samples

antibacterial activities and can be handled without posing any potential health risks. Nevertheless, it is advisable to handle such materials with appropriate protective measures.

4 Conclusion

In this study, we investigated the leaching behaviour and antibacterial activity of various waste materials, including waste from ready-mix concrete plant, precast industrial sludge, recycled alkali-activated material, municipal solid waste incinerated bottom ash, fly ash, high alumina tailings, and high magnesia tailings. Our findings shed light on the potential usability of these waste materials in construction while considering their environmental impacts and health-related aspects.

Regarding leaching behaviour, our results revealed that the waste materials released various ionic metals, with aluminium, potassium, and magnesium being the major ions commonly leached. Notably, MSWI FA and MSWI BA exhibited higher leaching levels of heavy metals compared to other materials. The leaching of aluminium, barium, chromium, lead, and zinc from MSWI fly ash and bottom ash was measured 28.7 ppm, 4 ppm, 3.9 ppm, 11 ppm, and 25 ppm, respectively. The leached heavy metals were within the recommended limits of EU, landfill legislation. The release of certain ions, such as calcium and sodium, from the waste materials may be related to their antibacterial properties, warranting further investigation into the potential applications in mitigating bacterial contamination.

The antibacterial activity of the waste materials was assessed using *E. coli* and *S. aureus* as representative bacteria. All samples demonstrated some level of antimicrobial activity against both bacterial strains. Notably, waste materials like RMC, RAAM, HA tailings, and HM tailings exhibited comparable inhibition power against *E. coli and S. aureus* (1.30 ± 0.03 cm). In contrast, municipal solid waste incinerated fly ash and bottom ash displayed a higher difference in inhibition between the two bacteria. The observed antibacterial behaviour could be attributed to the alkaline pH of the samples and the release of certain ions, which have been reported to influence bacterial growth and viability.

The conversion of waste materials into construction materials presents an opportunity to transition towards a circular economy. However, it is crucial to consider their leaching behaviour and potential antimicrobial properties to ensure environmental sustainability and human safety. Proper waste management practises, pre-treatment methods, and cautious handling should be employed when utilizing waste materials in construction applications. Future research should further explore the mechanisms behind the observed antibacterial properties and investigate the long-term effects of using these waste materials in construction to support sustainable and eco-friendly practises in the building industry.

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