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Low-cost preventative measures can effectively mitigate microplastic release from scientific research facilities in Antarctica

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Abstract

Microplastic release in Antarctica is an issue of increasing concern, despite the limited human presence in the region. This study estimates the annual release of microplastics from the wastewaters of scientific facilities through the use of personal care products and laundering. Furthermore, it analyses the most cost-efficient policy interventions to target this pollution. The study has estimated a potential release of 238 kg per year, which is negligible on a continental scale but could have substantial local environmental impacts. A comprehensive cost-efficiency analysis demonstrates that microplastic release can be effectively mitigated through low-cost preventative measures, such as installing washing machine filters and banning hygiene products containing microbeads. Furthermore, the implementation of wastewater treatment systems is suggested as a crucial and long-term cost-effective solution for treating wastewater effluent and removing other pollutants from the Antarctic region. These results provide a framework to inform policy decisions on microplastic release in Antarctica and lay the foundation for improved environmental protection strategies in this sensitive region.

Keywords: Antarctica; cost-efficiency analysis; microplastics; policy analysis; scientific facilities; wastewater

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Introduction

Antarctica was first discovered in 1820, and this was swiftly followed by periods of seal and whale exploitation in the region (Pearson *et al.* 2020). Following the end of the Heroic Age of Antarctic exploration, between *ca.* 1897 and 1922, levels of scientific activity were low until the preparations for the International Geophysical Year 1957/58 commenced, which saw the construction of a series of research facilities at locations around the continent (Berkman 2002). However, the inter-war period saw a substantial shore and ship-based whaling industry develop in the Antarctic Peninsula region (Brown 1963).

Since that time, human activities in the Antarctic region have increased, exerting increasing pressure on this once-pristine environment (Bargagli 2008, Caruso *et al.* 2022). A notable consequence of the increase in human activity is microplastic (particles smaller than 5 mm in size) pollution, which is a particular concern regarding the marine environment due to the challenges of removing such litter once it has been introduced and due to the potential impacts of microplastics on marine species and ecosystems (Rowlands *et al.* 2021).

Numerous sampling campaigns have confirmed the presence of microplastics in the Antarctic environment (Tirelli *et al.* 2022). These campaigns have found microplastics in both terrestrial (Aves *et al.* 2022, Jones-Williams 2025) and marine environments (Waller *et al.* 2017). Plastic pollution has been identified in near-surface marine samples (Cincinelli *et al.* 2017, Isobe *et al.* 2017, Absher *et al.* 2019, Lacerda *et al.* 2019, Suaria *et al.* 2020, Leistenschneider *et al.* 2021) as well as in seafloor sediments (Van Cauwenberghe *et al.* 2013, Munari *et al.* 2017, Reed *et al.* 2018, Cunningham *et al.* 2020).

Microplastics, if introduced into the environment, pose multiple risks to Antarctic marine ecosystems (Teuten *et al.* 2009, Sarkar *et al.* 2023). These particles can act as carriers of toxic chemicals, including additives from plastic production and persistent organic pollutants absorbed from surrounding waters (Campanale *et al.* 2020). Direct ingestion by marine organisms can cause physical blockages in digestive systems and facilitate the transfer of toxic compounds into tissues (Wright *et al.* 2013). Beyond the immediate physical effects, microplastics disrupt biological processes through endocrine interference and tissue damage, while their integration into food webs alters feeding behaviours and creates cascading ecological impacts (Egbeocha *et al.* 2018, Nelms *et al.* 2018). Notably, the presence of microplastics has been observed in Antarctic marine species, from smaller organisms, such as Antarctic krill (*Euphausia superba*; Wilkie Johnston *et al.* 2023, Zhu *et al.* 2023) and amphipods (Jones-Williams *et al.* 2020), to top predators such as fish (Cannon *et al.* 2016), penguins (Bessa *et al.* 2019) and seabirds (Auman *et al.* 2004).

Microplastics in Antarctica are sourced both locally and through ocean current transfer from outside the region (Aves *et al.* 2022). While the Antarctic Circumpolar Current (ACC) has traditionally been viewed as a barrier limiting the long-distance

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transport of debris from lower latitudes, studies have shown that it is more permeable than previously thought, allowing some plastic debris to cross into the Southern Ocean (Clarke *et al.* 2005, Thompson 2008, Fraser *et al.* 2017). Local sources of microplastic that may pollute the Antarctic environment are likely to come primarily from national scientific research facilities and tourism and fisheries vessels (Cincinelli *et al.* 2017, Munari *et al.* 2017, Hunter *et al.* 2024). Each source requires individual investigation to generate detailed information about microplastic release patterns from specific economic activities, enabling the development of more targeted and specialized mitigation measures. This study focuses specifically on microplastic release from wastewaters discharged by scientific stations in Antarctica.

As per the Council of Managers of National Antarctic Programs (COMNAP; COMNAP 2024), Antarctica has 102 research facilities encompassing 76 scientific stations, 5 refuges, 2 laboratories, 3 depots, 11 camps and 5 airfield camps. These facilities are operated by 31 nations. Daily operations within these facilities may contribute microplastics through wastewater, primarily in the form of microbeads, from personal/hygiene products such as toothpaste, shampoos, shower gels, detergents, cosmetics and fibres produced during the washing of synthetic textiles (Browne *et al.* 2011, Waller *et al.* 2017). Cosmetic products typically contain microbeads constituting between 0.5% and 6.0% of the product, with an average size of 250 μm (Zitko & Hanlon 1991, GESAMP 2015). A single washing load can release over 7 000 000 fibres into the water (Napper & Thompson 2016, De Falco *et al.* 2018). Associated microplastics can subsequently enter wastewater systems and potentially the environment if not treated properly (Magnusson & Norén 2014, Murphy *et al.* 2016).

The issue of microplastic release in wastewaters from research stations in Antarctica can be addressed through prevention measures to minimize their release and/or by implementing robust wastewater treatment systems (WWTSs) to treat wastewaters. WWTSs operate through the removal of physical, chemical and biological pollutants in three main stages (i.e. primary, secondary and tertiary treatment processes; Crini & Lichtfouse 2018, Sun *et al.* 2019). In the primary stage, methods such as mechanical processes, maceration and sedimentation are employed to eliminate solid wastes, fats, oils and grease from the wastewater stream. The secondary stage involves converting dissolved biological matter into a solid mass using waterborne microorganisms, which can be disposed of or reused. The methods used here include activated sludge, fluidized bed reactors, filter beds, biological aerated filters or membrane biological reactors (Krzeminski *et al.* 2019). Tertiary treatment focuses on disinfecting treated water using chemical or physical methods such as microfiltration, chemical precipitation, chlorine, ultraviolet (UV) radiation or ozone, before discharging the final effluent into the natural environment (de Boer *et al.* 2022).

Although WWTSs are not primarily designed for microplastic waste removal, they can effectively capture microplastic particles during settling, aeration and filtration processes. Current studies suggest that primary WWTSs can remove between ~35% and 98.4% of microplastics (Prata 2018, Sun *et al.* 2019). Following primary treatment, secondary WWTSs can contribute to further reductions of 0.2–14% of original total microplastics (Hu *et al.* 2019, Iyare *et al.* 2020). Removal efficiency levels fluctuate depending on factors such as treatment techniques, influent volume and microplastic dimensions. Lastly, some tertiary WWTS techniques can further decrease microplastic content to as low as 0.2% relative to initial content after primary and secondary treatment (Ngo *et al.* 2019, Reza *et al.* 2023).

The internal practices and policies of scientific stations, as well as the operations of WWTSs in Antarctica, remain weak at this time. Disposal of all waste types within the Antarctic Treaty area is considered through the Protocol on Environmental Protection to the Antarctic Treaty, which was signed in 1991 and entered into force in 1998. Through Annex III to the Protocol, entitled 'Waste disposal and waste management', minimum standards regarding sewage treatment and disposal into the Antarctic environment were established, with no mandatory regulations in place requiring scientific facilities to treat their wastewaters any more than via simple maceration (Connor 2008).

In recent years, the problem of microplastic pollution in Antarctica has started to gain more attention. The issue of microplastic pollution was first presented to a meeting of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Working Group on Ecosystem Monitoring and Management in 2016 (CCAMLR 2016), where the assessment of the presence and impacts of microplastics and nanoplastics (size: 1 nm–1 μm) on Antarctic marine biota was discussed. Since then, plastic pollution has been considered within the Committee for Environmental Protection and Antarctic Treaty Consultative Meetings (ATCM; ATCM 2019). In 2019, a non-binding resolution was agreed upon entitled 'Reducing plastic pollution in the Antarctic and Southern Ocean' that encouraged parties to eliminate personal care products containing microplastic beads in the Antarctic Treaty area, share information on methods to reduce microplastic release from wastewater systems, support greater monitoring of plastic pollution, invite the Scientific Committee on Antarctic Research (SCAR) to report on any new information on the risks of plastic pollution and consider the issue of plastic release in any future revisions of the Annexes to the Protocol (https://www.ats.aq/devAS/Meetings/Measure/705).

To date, little economic and policy analysis has been conducted to support ATCM policy decisions on microplastic release in Antarctica. The objective of this paper is to identify the most economically efficient solution to mitigate and reduce microplastic pollution production in wastewaters and their release in the Antarctic environment as a result of research and science support activities. First, we estimated the release of microplastics into the Antarctic environment as a result of scientific activities at the continent's research facilities. Second, a cost-efficiency analysis (CEA) was performed whereby different microplastic waste management options designed to mitigate the problem were evaluated.

Materials and methods

Microplastic pollution from scientific facilities' wastewaters

Estimation of the potential production of microplastics in wastewaters

For this analysis, the two major sources of microplastic in wastewaters were considered (i.e. hygiene products and laundry). To estimate the amount of microplastics produced from an Antarctic research facility in wastewater each year ($M^{prod(s)}$; mg/year), three inputs were required: 1) the quantity of microplastics contained in personal care products used per person ($M^{prod}_{(P)}$; mg/person/day) and laundering($M^{prod}_{(L)}$; mg/person/day), 2) the mean population size in each Antarctic facility (p^s) and 3) the number of days spent by the population in each facility(t^s). Once these inputs were

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obtained, the potential production of microplastics in wastewater was estimated using Equation 1.

$$\left(M^{prod}_{(P)} + M^{prod}_{(L)}\right) * p^{s} * t^{s} = M^{prod(s)} \quad (1)$$

Here, the subscript $'s'$ represents the scientific facility in question. To estimate the total amount of microplastics produced by all the facilities, we simply summed the microplastic production from each facility, as depicted in Equation 2.

$$\sum_{s=1}^{102} M^{prod(s)} \quad (2)$$

Finding primary data for these inputs was challenging, as there are currently no empirical data on the quantities of microplastic production or accumulation at Antarctic wastewater treatment stations due to day-to-day activities. To estimate potential contributions, we therefore used published rates of microplastic generation per person from other regions (from hygiene products and laundering) and applied these rates to scientific bases in Antarctica, a method also suggested by Waller *et al.* (2017). Although the Antarctic ecosystem is unique, our method is based on the assumption that scientists stationed there maintain similar daily life patterns as in their home countries. However, it is important to note that these estimates can vary depending on individual habits, product choices and specific station protocols. Despite this variability, existing data from non-Antarctic regions provide the best available proxies for assessing microplastic release from these stations, given the current lack of Antarctica-specific measurements. However, to address uncertainties, we considered three levels of microplastic production: low, medium and high. The medium estimate represented the mean production rate presented in all of the published studies considered for a given microplastic source, whereas the low and high estimates were derived from studies that provided the lowest and highest microplastic production rates, respectively. Estimations of the rates of microplastic production from the use of personal care products ranged from 2.4 to 27.5 mg/person/day, based on studies by Gouin *et al.* (2015) and Napper *et al.* (2015). Similarly, estimates of synthetic fibres produced through laundering vary, with studies reporting between 107 and 1286 mg/day/person (Browne *et al.* 2011, Napper & Thompson 2016, Pirc *et al.* 2016, Hernandez *et al.* 2017, De Falco *et al.* 2018, 2019, Yang *et al.* 2019, Cai *et al.* 2020).

Population data and data on the time spent by that population at each facility were sourced from the COMNAP database (COMNAP 2022), which detailed the peak population in each of the scientific facilities and the level of occupancy by personnel during the summer and winter. Antarctica contains 41 permanent facilities (i.e. operational year-round) and 61 summer facilities that are generally open for a maximum of 5 months annually. The level of station occupancy and duration of opening are dependent upon the scientific and logistical requirements of the nation operating the facility each year. As detailed information on occupancy was not available for all of the facilities under consideration, the following assumptions were made: during the 5 months of summer, peak population was reached, while during the 7 months of winter, ~25% of the peak population was assumed to be residing in each facility. Therefore, to calculate the number of person-days on the station, for summer-only facilities the peak population was multiplied by 151 days (i.e. 5 months), whereas for year-round facilities the peak population was multiplied by 151 days (i.e. 5 months) plus 25% of the peak population present for the remainder of the year (i.e. 7 months or 214 days).

Estimation of the potential level of microplastic release into the environment (encompassing areas of permanent ice and the marine environment)

Once the potential amount of microplastics produced by facilities was calculated, we calculated the proportion that was not treated and likely to be released into the environment. To achieve this, the microplastic removal efficiency of each facility' WWTSs was estimated. The removal efficiency rate estimate depended mainly upon the presence and characteristics of the WWTSs installed at each facility.

The plastic released from each facility was estimated using Equation 3.

$$M^{prod(s)} - \left(M^{prod(s)} * E^{s}\right) = M^{rel(s)} \quad (3)$$

As shown earlier, the amount of microplastics removed by the WWTSs annually can be estimated by multiplying by the amount of microplastics produced within the facility each year ($M^{prod(s)}$) by the microplastic waste removal efficiency of a facility (E^{s}; %). This allows estimation of the potential release of microplastics into the environment from a given facility each year ($M^{rel(s)}$; mg/year).

At facilities without any WWTSs, it was assumed that all microplastics produced on station from personal products and laundering were released into the environment.

The total amount of microplastics released into the Antarctic environment was estimated by summing the amounts released from each facility, as represented in Equation 4.

$$\sum_{s=1}^{102} M^{rel(s)} \quad (4)$$

Data for the calculation of microplastic release were collected as follows. To estimate the efficiency of microplastic removal, a comprehensive list of wastewater treatment methods used at Antarctic facilities was compiled based on data collected from the COMNAP survey (COMNAP 2022). This survey was developed with the support of a scientific group and the COMNAP, and it was distributed to managers of 84 scientific facilities in Antarctica to gain insights into the WWTSs within each facility. Out of the 84 facilities about which information was sought, survey data were received for 66 of them. Among these responses, 46 facilities reported the presence of WWTSs. Within this group of 46 facilities, 31 indicated the installation of tertiary WWTSs, primarily through ozone and UV treatment. Eight facilities had only primary and secondary WWTSs, while seven were solely filtering waste at the primary level before releasing it into the Antarctic environment. However, due to confidentiality agreements, detailed data on the filtration systems used by each facility and country cannot be provided. Therefore, the results have been presented on a regional basis rather than on a station-by-station basis (i.e. East Antarctica, Antarctic Peninsula, Ross Sea region and Queen Maud Land).

Due to the absence of data for some facilities, it was assumed that microplastics from these facilities were directly released into the environment. In addition, in the calculations, it was assumed that if a facility had a WWTS, then the system was operational

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throughout the year. However, at some facilities, despite WWTSs having been installed, national operators may choose not to operate them year-round, particularly during periods of reduced population, such as the winter season.

After collecting data on the type of WWTSs installed by each facility, a literature review was conducted to estimate the average removal efficiency associated with each treatment method. At present, there is a lack of data and understanding regarding the potential removal of microplastics through WWTSs installed in Antarctica. However, detection of microplastics in WWTS effluents has been reported throughout the world, including in Asia, Europe, the USA, Australia, China and Russia (Prata 2018). Antarctica's research facilities, which employ similar primary WWTSs, mainly include methods such as screening, grit removal, sedimentation and settling tanks. These techniques are particularly effective at removing larger microplastics, specifically those sized between 1000 and 5000 μm (Lofty *et al.* 2022), with an estimated mean removal efficiency of 71% (Talvitie *et al.* 2017a, Ziajahromi *et al.* 2017, Lares *et al.* 2018, Wang *et al.* 2018, Hidayaturrahman & Lee 2019, Lv *et al.* 2019, Yang *et al.* 2019, Zhang *et al.* 2020). In facilities with secondary WWTSs in place along with a primary system, the overall mean removal efficiency varies by method: coagulation and flotation achieve 89.0% (Wang *et al.* 2017, Zhang *et al.* 2020), activated sludge achieves 87.2% (Talvitie *et al.* 2017b, Lares *et al.* 2018, Simon *et al.* 2018, Hidayaturrahman & Lee 2019), aeration achieves 78.1% (Ziajahromi *et al.* 2017, Simon *et al.* 2018, Liu *et al.* 2019), membrane bioreactors achieve 90.2% (Talvitie *et al.* 2017, Ziajahromi *et al.* 2017, Lares *et al.* 2018, Lv *et al.* 2019), secondary settling tanks achieve 97.0% (Dris *et al.* 2018, Lv *et al.* 2019) and anaerobic-anoxic-aerobic (A2O) treatments achieve 54.7% (Murphy *et al.* 2016, Jia *et al.* 2019, Liu *et al.* 2019, Lv *et al.* 2019, Edo *et al.* 2020).

For facilities with tertiary WWTSs, the percentage of microplastics removed in the first two stages is observed, and then stage-wise removal efficiency is applied based on the tertiary treatment method used. The estimated mean removal efficiencies for tertiary treatment methods are as follows: sand filtration/rapid filtration achieves 61.0% (Talvitie *et al.* 2017a, Mintenig *et al.* 2017, Wang *et al.* 2017, Pivokonsky *et al.* 2018, Hidayaturrahman & Lee 2019, Zhang *et al.* 2020), ultrafiltration achieves 41.7% (Ziajahromi *et al.* 2017, Liu *et al.* 2020, Tadsuwan & Babel 2022), reverse osmosis achieves 25.0% (Wang *et al.* 2017, Ziajahromi *et al.* 2017), activated carbon achieves 47.6% (Wang *et al.* 2017, Ziajahromi *et al.* 2017, Pivokonsky *et al.* 2018), ozone achieves 69.8% (Hidayaturrahman & Lee 2019Yang *et al.* 2019), UV achieves 71.7% (Jia *et al.* 2019, Yang *et al.* 2019, Easton *et al.* 2023), denitrification achieves 71.7% (Yang *et al.* 2019, Edo *et al.* 2020) and membrane disk-filters achieve 79.4% (Hidayaturrahman & Lee 2019, Simon *et al.* 2019).

Policy analysis to reduce microplastic pollution from scientific facilities

Antarctica is governed by the 29 Consultative Parties to the Antarctic Treaty. Implementing large-scale, high-cost measures may not be feasible or acceptable. Therefore, as an initial step, we believe it could be valuable to explore low-cost, low-effort solutions that do not impose financial burdens or cause resistance from stakeholders. The financial cost of reducing the release of microplastics into the Antarctic environment was examined under five microplastic waste management options. Each management option utilized a different wastewater treatment measure or combination of measures aimed at reducing microplastic release (see Table I).

Management Option 1 has primary and secondary treatment only, while Management Option 2 incorporates tertiary treatment methods. Management Option 3 is similar to Management Option 1 but includes the installation of washing machine filters, which are designed to capture microplastic fibres produced during clothes laundering. Management Option 4 is similar to Management Option 1 but includes the implementation of a ban on hygiene products containing microbeads. Finally, Management Option 5 combines the installation of washing machine filters with a ban on personal hygiene products containing microbeads, but no wastewater treatment methods are employed.

To compare the proposed management options, CEA was used. CEA is a method of input-allocative efficiency analysis used to compare different policy investment scenarios by assessing and finding the optimal allocation of input in a way that minimizes cost (Camanho *et al.* 2024). In this study, our objective was to identify the optimal microplastic removal strategies for every dollar spent. To achieve this, the amount of microplastics produced by one individual annually was compared with the annual cost of providing wastewater treatment for that individual.

The cost-efficiency (*CE*) of each management option was assessed by determining the ratio of benefit received and cost spent. This was evaluated using Equation 5.

$$CE = \frac{E^{Y'}}{C^{Y'}} \times 100 \tag{5}$$

Table I. Summary of microplastic waste management options with different combinations of measures.

Management option	Management measures	
	Wastewater treatment management	Microplastic limitation
1	1^{o} and 2^{o}	-
2	1^{o}, 2^{o} and 3^{o}	-
3	1^{o} and 2^{o}	Washing machine filters
4	1^{o} and 2^{o}	Ban on hygiene products with microbeads
5	-	Washing machine filters and ban on hygiene products with microbeads

1^{o} = primary; 2^{o} = secondary; 3^{o} = tertiary.

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This equation represents the yearly benefit (i.e. amount of microplastics removed in grams $\left(E^{Y}\right)$ per unit of cost (C^{Y})). The prime notation (‘) signifies that the data are presented on a per-person basis.

To compare each management option, we calculated the total cost and total positive outcome received per person annually with each option.

For cost data, we considered the yearly financial cost per person of a WWTS in US dollars. The total financial cost of each treatment method was estimated by dividing the fixed installation cost of a WWTS $\left(C_{fix}\right)$ by its lifespan $(l(Y))$before it becomes obsolete and then adding this to the yearly maintenance cost (C_{var}). This is represented by Equation 6.

$$\frac{C^{Y} = \frac{C_{fix}}{l(Y)} + C_{var}}{cap} \tag{6}$$

To estimate the cost of each WWTS per person, the total cost was divided by the total number of station personnel that can be supported by the WWTS (cap). Equation 6 was applied to each management option, depending on the different costs associated with different treatment method sets.

The indicator of benefits is the amount of microplastics removed by the treatment method. To calculate this, first we calculated the average amount of microplastics produced by a single individual. This was calculated simply by dividing the total amount of microplastics produced by all stations in a year by the total population, as presented by Equation 7.

$$\frac{\sum M^{prod(s)}}{\sum p^{s}} = M^{prod'}, \text{ where } s = 1, \ldots, 102 \tag{7}$$

Once we calculated the amount of microplastics produced by one person in a year, we were able to determine, for each management option, how much microplastic could be removed. The amount of microplastics removed from each management option was estimated as described below.

$$\underbrace{\left\{\left[M^{prod'} - \left(M^{prod'} \times E^{prim}\right)\right] \times E^{sec}\right\}}_{\text{Microplastic removed from secondary WWTS}} + \underbrace{\left(M^{prod'} \times E^{prim}\right)}_{\text{Microplastic removed from primary WWTS}}$$

(Management Option 1)

In Management Option 1, the total amount of microplastics produced initially underwent primary treatment. The removal efficiency rate of the primary WWTS $\left(E^{prim}\right)$ was multiplied by the total amount of microplastics produced per person in a year $\left(M^{prod'}\right)$. Subsequently, the remaining microplastics flowed through the secondary WWTS, where it underwent further cleaning using the removal efficiency rate of the secondary WWTS (E^{sec}).

$$\underbrace{\left\{\left\{\left[M^{prod'} - \left(\left(M^{prod'} - \left(M^{prod'} * E^{prim}\right)\right) \times E^{sec}\right)\right]\right\} + \left(M^{prod'} \times E^{prim}\right)}_{\text{Microplastics removed from tertiary WWTS}} \times E^{ter}\right\} + \Bigg(\underbrace{\left(M^{prod'} - \left(M^{prod'} \times E^{prim}\right)\right)}_{\text{Microplastics removed from secondary WWTS}} \underbrace{\times E^{sec}\Bigg)}_{\text{Microplastics removed from primary WWTS}}$$

(Management Option 2)

In Management Option 2, wastewater underwent an additional tertiary treatment. Here, the removal efficiency of the tertiary WWTS $\left(E^{ter}\right)$ was applied to the remaining wastewater after it passed through the primary and secondary treatment systems.

$$\underbrace{\left\langle\left\{M^{prod'} - \left[\left(M_{(P)}^{prod'} + \left(M_{(L)}^{prod'} - \left(M_{(L)}^{prod'} \times E^{filters}\right)\right)\right) \times E^{prim}\right]\right\} \times E^{sec}\right\rangle}_{\text{Microplastics removed from secondary WWTS}} + \underbrace{\left\langle\left(M_{(L)}^{prod'} \times E^{filters}\right)\right\rangle}_{\text{Microplastics removed from washing machine filters}} + \underbrace{\left\langle\left(M_{(L)}^{prod'} - \left(M_{(L)}^{prod'} \times E^{filters}\right)\right) \times E^{prim}\right\rangle}_{\text{Microplastics removed from primary WWTS}}$$

(Management Option 3)

In Management Option 3, before wastewater underwent treatment in the main WWTSs, a portion of the microplastics produced during laundry activities was removed through washing machine filters. This removal was estimated by multiplying the removal efficiency rate of the washing machine filters $\left(E^{filters}\right)$ by the amount of microplastics produced during laundering $\left(M_{(L)}^{prod'}\right)$. The remaining microplastics were then released into the wastewater along with the microplastics from other sources $\left(M_{(P)}^{prod'}\right)$. Subsequently, the removal efficiency rates of the primary and secondary WWTSs were applied, as explained previously.

$$\underbrace{\left\{\left[M_{(L)}^{prod'} - \left(M_{(L)}^{prod'} \times E^{prim}\right)\right] \times E^{sec}\right\}}_{\text{Microplastics removed from secondary WWTS}} + \underbrace{\left(M_{(L)}^{prod'} \times E^{prim}\right)}_{\text{Microplastics removed from primary WWTS}} + M_{(P)}^{prod'}$$

(Management Option 4)

In Management Option 4, it was assumed that with the ban on products containing microbeads there was no production of microplastics from this source. Thus, only the microplastic

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Table II. Input data collected for wastewater treatment systems (WWTSs) at Rothera Research Station.

	Primary and secondary WWTSs	Tertiary WWTSs	Washing machine filters
Lifespan	50 years	20 years	20 years
Fixed cost	\$1 329 429	\$12 465	\$3740
Annual cost	\$15 000	\$15 714	\$623

production from laundry underwent wastewater treatment through the primary and secondary systems. As a result, microplastic removal under Management Option 4 was the amount that was removed through primary and secondary WWTSs plus the amount that was eliminated through the ban on hygiene products with microbeads.

$$\left(M_{(L)}^{prod'} \times E^{filters} \right) + M_{(P)}^{prod'} \qquad \text{(Management Option 5)}$$

Finally, in Management Option 5, the microplastics produced from laundering underwent treatment through washing machine filters. The remaining wastewater, along with any microplastics it may have contained, was directly released into the environment, as there were no other WWTSs in place. The total benefit received was the amount that was removed through primary and secondary wastewater treatment plus the amount that was eliminated through banning hygiene products with microbeads.

Initial inquiries showed that it would be difficult to gather data on the cost of WWTSs from each Antarctic facility. Estimates of the fixed and variable costs associated with the primary, secondary and tertiary WWTSs, as well as washing machine filters, were based on those for the WWTSs installed in Rothera Research Station, Adelaide Island, Antarctic Peninsula. Information was obtained through interviews with British Antarctic Survey estate managers. These data were then extrapolated to all other stations, assuming that the cost of WWTSs for one person at Rothera Research Station was approximately consistent across all stations.

At the time of this study, Rothera Research Station was equipped with primary, secondary and tertiary WWTSs capable of treating wastewater generated by up to 110 individuals, and it operated 11 laundering machines on which microplastic filters were being installed. The input data used for the calculations are presented in Table II.

While the costs of all treatment levels and washing machine filters were estimated, the cost of banning products containing microbeads was assumed to be zero. In this study, only the immediate financial burdens on research stations were considered. While switching to microplastic-free hygiene products may result in minor costs or savings to national operators, these secondary financial effects or opportunity costs were beyond the scope for this study due to a lack of data and varying product pricing across countries.

A literature review was undertaken to estimate the average removal efficiency rate for each level of wastewater treatment (i.e. primary, secondary and tertiary). A total of 20 different studies were consulted to assess the influent and effluent of microplastics in various WWTS types. Based on the mean values calculated from these studies, the removal efficiencies of microplastics used in the calculations were 71% for primary WWTSs (Talvitie *et al.* 2017a, Ziajahromi *et al.* 2017, Lares *et al.* 2018, Wang *et al.* 2018, Hidayaturrahman & Lee 2019, Lv *et al.* 2019, Yang *et al.* 2019, Zhang *et al.* 2020), 92% for secondary WWTSs (Magnusson & Norén 2014, Carr *et al.* 2016, Talvitie *et al.* 2017a,b, Ziajahromi *et al.* 2017, Dris *et al.* 2018, Lares *et al.* 2018, Simon *et al.* 2018, Wang *et al.* 2018, Hidayaturrahman & Lee 2019, Liu *et al.* 2019, Lv *et al.* 2019, Yang *et al.* 2019, Zhang *et al.* 2020, Franco *et al.* 2021) and 98% for tertiary WWTSs (Mintenig *et al.* 2017, 2019, Talvitie *et al.* 2017a, Ziajahromi *et al.* 2017, Pivokonsky *et al.* 2018, Wang *et al.* 2018, Hidayaturrahman & Lee 2019, Lv *et al.* 2019, Ma *et al.* 2019, Yang *et al.* 2019, Li *et al.* 2020).

Similarly, we applied the same method to evaluate the removal efficiency of washing machine filtration. After reviewing six studies on microplastic filters, the mean removal efficiency was calculated to be 94% (Brodin *et al.* 2018, McIlwraith *et al.* 2019, Napper *et al.* 2020, Erdle *et al.* 2021, Le *et al.* 2022, Belzagui *et al.* 2023).

Once the 'yearly per person costs' and 'benefits' for each management option were estimated, comparisons were made based on monetary estimates of physical outcomes, forming the basis for policy recommendations.

Results and discussion

Microplastic production and release from scientific facilities' wastewaters

The estimates of annual microplastic production of research facilities were categorized into four regions: East Antarctica, Antarctic Peninsula, Ross Sea region and Queen Maud Land, as shown in Table III, which presents the detailed results on the quantity of microplastics produced by scientific facilities in each region.

The highest amount of microplastic was produced by facilities located in the Antarctic Peninsula, which was because of the large number of facilities in the region. The Ross Sea region was the second largest producer of microplastic. Despite comprising only 13% of the total number of facilities, the region hosted 1722 individuals during the summer. Approximately half of the facilities were operated by the USA and accommodated 77% of the region's population. The East Antarctica region had the second highest number of facilities and the third highest level of microplastic production. Lastly, Queen Maud Land had the smallest number of facilities, the lowest population and the lowest amount of microplastic production.

According to mean estimations, scientific facilities in Antarctica produced a total of 344 kg of microplastics from personal hygiene products and laundering clothes annually. Out of this, ~238 kg/year, constituting 69% of the amount produced, was released into the Antarctic environment due to the lack or limited capabilities of WWTSs currently employed at Antarctic facilities.

Despite the Antarctic Peninsula region having the highest population and number of facilities, it was not the primary region contributing to microplastic pollution in the Antarctic environment. The Ross Sea region potentially contributed the highest amount of microplastic to the environment, estimated at ~92 kg/year.

The Antarctic Peninsula region ranked as the second largest contributor to microplastic pollution. This region had a lower

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Table III. Summary of estimated annual microplastic production at Antarctic research facilities and the quantity of microplastic released in wastewater into the environment by scientific facilities in different Antarctic regions (kg/year).

	East Antarctica	Antarctic Peninsula	Rose Sea region	Queen Maud Land	Total
Number of facilities	26	51	13	12	102
Peak population	1256	2011	1722	720	5709
Microplastic production in wastewater, mean in kg (low/high)	73 (23/313)	126 (44/537)	103 (36/442)	42 (15/178)	344 (121/1470)
Microplastic release in environment, mean in kg (low/high)	32 (11/137)	80 (28/343)	92 (32/391)	34 (12/146)	238 (83/1017)

Table IV. Cost-efficiency of different microplastic waste management options.

	Option 1	Option 2	Option 3	Option 4	Option 5
Annual cost per person per year (US dollars)	378	527	446	378	68
Removal efficiency (for 1 person per year in grams)	55.40	59.10	59.10	55.67	48.92
Removal efficiency per US dollar	15%	11%	13%	15%	72%

proportion of stations with WWTSs compared to the other regions. However, half of its facilities are seasonal, some of which host small populations of, for example, eight or fewer individuals. This renders it economically and technically unfeasible to install sewage treatment plants. Consequently, the minimal microplastic production from these populations is directly discharged into the environment.

Lastly, East Antarctica and Queen Maud Land exhibited lower microplastic release rates, estimated at ~32 and 34 kg/year, respectively, compared to the Ross Sea region and Antarctic Peninsula. The COMNAP survey data indicated that these regions had high proportions of facilities equipped with tertiary WWTSs, indicating more effective wastewater management practices.

Figure 1 provides a geographical representation of the distribution density of scientific stations in Antarctica and the corresponding quantities of microplastics produced and released by these stations. The majority of the stations are situated near the coast, increasing the likelihood of immediate marine environmental impacts.

Policy analysis to reduce microplastic pollution from scientific facilities

The results of the CEA are presented in Table IV, and they illustrate the optimal investment options and the cost-efficiency for each US dollar spent across various management options.

Management Option 5, which targeted the removal of microplastics at the source, emerged as the most cost-efficient option. This outcome is consistent with recent studies that have shown that intervening at earlier stages to minimize microplastic release is less costly and yields higher removal rates compared to options in which microplastic particles are allowed to accumulate in large quantities within wastewater, which subsequently necessitates costly cleaning processes (Vuori & Ollikainen 2022, Hettiarachchi & Meegoda 2023). This low-cost option could be an effective solution to deal with microplastic release from stations with low populations, such as many of the facilities found in the Antarctic Peninsula.

Furthermore, both Management Option 1 (incorporating only primary and secondary WWTSs) and Management Option 4 (adding a ban on products containing microbeads alongside primary and secondary WWTSs) delivered similar levels of microplastic removal, with Management Option 4 only slightly outperforming Management Option 1. This comparable performance can be explained by the fact that both options use the same WWTSs to target the majority (estimated at 94%) of microplastics, which originate from laundering synthetic clothes. Thus, the cost of removing the major part of microplastics is similar in both options.

However, Management Option 4 merits greater attention because it completely eliminates the remaining 6% of microplastic releases by banning products containing microbeads. This additional benefit is achieved with minimal or no immediate cost to research stations, thus increasing its cost-efficiency.

Finally, Management Option 2 (incorporating primary, secondary and tertiary WWTSs) and Management Option 3 (with primary and secondary WWTSs plus installation of washing machine filters) achieve nearly identical microplastic removal rates (59.10 g/person/year). Management Option 3 proved to be more economically advantageous, as a tertiary WWTS requires significant investment compared to the installation of washing machine filters. However, these results do not intend to advocate against the importance of tertiary WWTSs. It is crucial for the facilities, especially those with large populations, such as some of those in Ross Sea region, to install tertiary-level WWTSs. This study specifically addresses microplastic waste, but it is essential to acknowledge that wastewater contains other biological and chemical pollutants that can significantly impact the Antarctic environment and its biodiversity (Akpor *et al.* 2014). Wastewater, especially from toilets, may contain pathogens such as bacteria and viruses (Lou *et al.* 2021). Tertiary WWTSs are necessary to remove these pollutants effectively. If all of these other pollutants are considered, Management Option 2 presents the highest cost-efficiency rate, as no other management option fully addresses both biological and chemical pollutants. Additionally, this study does not account for the secondary impacts of microplastics, such as the release of chemicals, which would further increase the cost-efficiency of tertiary WWTSs.

Study limitations

Several limitations should be acknowledged for future research considerations. This study focused exclusively on policy

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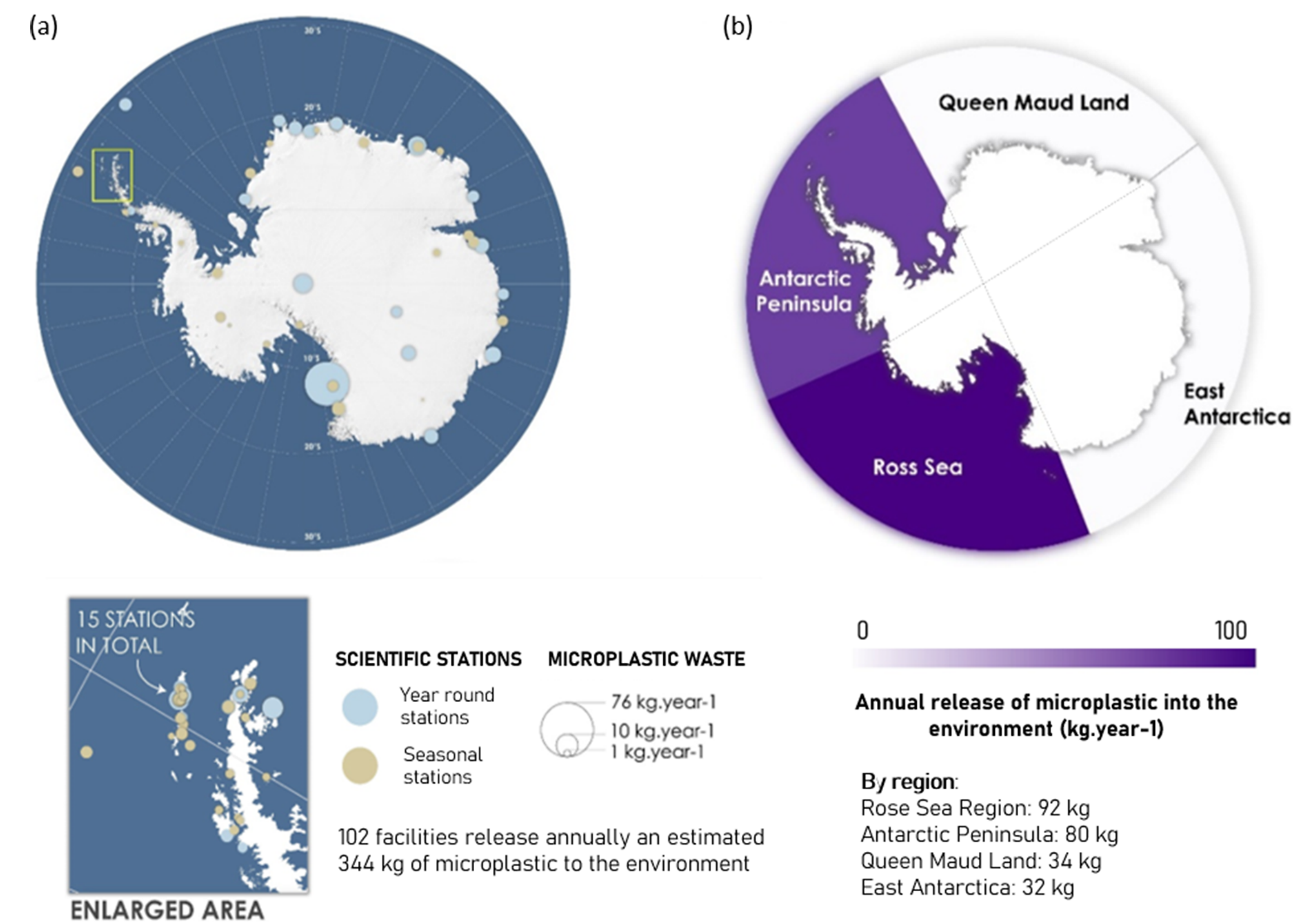

Figure 1. Maps showing potential microplastic pollution from scientific facilities in Antarctica: (a) representation of the mass of microplastic produced at each facility per year; (b) estimation of the quantity of microplastic released into the Antarctic environment within each region (i.e. into ice shelves, ice sheets and the marine environment).

interventions targeting microplastic generation through banning personal hygiene products containing microbeads. However, other upstream prevention strategies (e.g. replacing synthetic clothing with natural fibres or reducing human presence in Antarctica) were not considered due to practical constraints. Synthetic fabrics provide essential thermal protection and safety features critical for Antarctic conditions that natural, bulky alternatives cannot currently match without compromising personnel safety. Similarly, reducing scientific presence was determined to be counterproductive to our broader scientific and environmental goals. The research conducted in Antarctica provides irreplaceable data on climate change, marine ecosystems and global environmental processes. These approaches will reduce one form of impact while potentially creating greater harms through compromised safety or scientific understanding.

Nevertheless, it remains important to further investigate the microplastic emissions associated with these upstream sources, as research stations contribute microplastic particles through multiple pathways beyond WWTSs (Frontier *et al.* 2025). Notably, Napper *et al.* (2023) demonstrated that atmospheric deposition of synthetic microfibres shed during normal textile use represents a significant pathway for microplastic pollution - potentially exceeding the quantities released during laundering. Given the extensive use of synthetic clothing and equipment by scientists working in Antarctic conditions, there is probably a substantial direct release of microfibres into the environment through daily wear and tear, independent of washing processes. This significant source of contamination requires further research as our understanding of microfibre shedding patterns during daily use continues to evolve.

Furthermore, to develop a comprehensive understanding of microplastic contamination in this sensitive region, it is crucial to investigate other significant contributors - particularly tourism and fishing operations, both of which have increased substantially in recent years. Antarctic tourism has grown dramatically, with visitor numbers rising from ~8000 in the early 1990s to over 122 000 in the 2023/2024 season before the COVID-19 pandemic (International Association of Antarctica Tour Operators 2024). Each vessel carries washing machines, shower facilities and other amenities that generate wastewater. Unlike research scientific stations, these vessels typically employ less sophisticated WWTSs due to space constraints and operational limitations at sea, potentially resulting in higher concentrations of microplastic discharge directly into Antarctic waters.

Similarly, fishing activities in the Southern Ocean have intensified. These operations introduce microplastics through multiple pathways: degradation of fishing nets, wastewater from crew facilities and inadvertent release of operational waste. A study by Waller *et al.* (2017) estimated that a single fishing vessel might release up to 5.6 billion microplastic particles annually through equipment degradation alone.

Conclusion

To target the microplastic problem, it is essential to study each sector and source independently in order to be able to develop focused and efficient mitigation strategies. This study focused on estimating the potential microplastic release from scientific facilities in Antarctica and investigated possible solutions to manage wastewater flow. Annually, an estimated 238 kg of microplastic particles are released by these stations. On a continental scale - covering 14 million km^2 - this amount might seem negligible. However, the continuous release of microplastics can have a significant local impact over time, particularly in areas near the stations where dilution and dispersal rates of wastewater are low.

The study has also shown that this microplastic pollution can be effectively addressed by prioritizing simple, low-cost preventative methods. Some solutions involve simple technologies such as washing machine filters and changes in behaviour at stations by placing a ban on hygiene products containing microbeads. Additionally, we recommend the general improvement of sewage treatment facilities for the long-term preservation of the Antarctic environment. Comprehensive wastewater treatment is crucial for eliminating other pollutants such as pathogens, metals, organic matter and microplastic particles.

Currently, Antarctica lacks specific regulations or a continent-wide monitoring programme to address microplastic pollution (Waller *et al.* 2017). As part of the United Nations Sustainable Development Goals, the Southern Ocean Action Plan identified the improvement of waste management in this region as a critical priority (Janssen *et al.* 2022). The empirical results of this study are intended to help improve current decisions regarding microplastic waste in Antarctica.

Finally, this research offers a methodological foundation for broader applications, including future assessments of microplastic emissions from other human activities such as fisheries and tourism. Expanding this framework could help us to achieve a more comprehensive understanding of microplastic sources and guide effective protection strategies for the Antarctic environment.

Our study provides a framework to inform policy decisions on microplastic release in Antarctica and lays the foundation for improved environmental protection strategies in this sensitive region.

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Author contributions. Aanchal Jain: conceptualization, methodology, data curation, writing. Kevin A. Hughes: data curation, writing, supervision. Clara Manno: conceptualization, data curation, writing, supervision, resources. All authors reviewed the manuscript.

Data availability. All the data presented in this study are available in this paper.

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Competing interests. The authors declare none.

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