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Life cycle assessment of manual toothbrush materials

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Abstract

Background A manual toothbrush is an indispensable tool for promoting and maintaining oral health worldwide but given the non-biodegradable and non-recyclable thermoplastic materials from which it is made, it cannot be considered free of threats to the environment. Therefore, also in light of the World Dental Federation's goals to implement and initiate policies for sustainable dentistry, this study evaluates the sustainability of two materials most used for manual toothbrush bristles, namely nylon, and silicone.

Objectives The objective is to investigate the optimal solution to reduce the environmental impact of toothbrushes, and how the environmental impact would change if only the brush head was changed instead of the entire toothbrush.

Methods Life Cycle Assessment and Carbon Footprint were used. Four manual toothbrushes with nylon bristles, and a handle in polypropylene with/without silicone parts (N1, N2, N3, N4) and two manual toothbrushes, with silicone bristles, but one with polypropylene handle only (Si1), the other with polypropylene handle and silicone parts (Si2) were evaluated.

Results A toothbrush with silicone bristles is more sustainable than one with nylon bristles in all 18 impact categories, with average values of – 14%. In addition, eliminating only the brush head instead of the entire toothbrush could result in savings of 4.69×10^{-3} kg CO_2 eq per toothbrush. Therefore, based on the results of this study and to meet Dentistry's need to reduce its environmental impact, the ideal toothbrush should be lightweight, with less superfluous material, and with less impactful materials such as silicone instead of nylon.

Conclusions The concluding indications for improving the sustainability of toothbrushes are therefore: (i) eliminate the amount of superfluous material; (ii) develop lighter models; and (iii) develop models in which only the brush head is replaced rather than the entire toothbrush.

Keywords Polymers · Health services research · Dental public health · Dental hygiene · Consumer healthcare products

1 Introduction

As of July 2021, with Directive (EU) 2019/904 [1], the European Union has banned the use of single-use plastic items, as part of an EU policy to implement measures to protect the environment, both marine and terrestrial, and to contain the rise in global temperatures to below + 2 °C compared to the pre-industrial era. In this regard, current estimates of the total amount of plastic material consumed each year in Europe, some of which ends up in the seas, leading to the worrying estimate of the largest volume of plastic in the Mediterranean by 2050 [2]. In light of this

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geopolitical and economic context, the FDI World Dental Federation (FDI) has also set its 2030 agenda to implement and initiate policies for the advent of Sustainable Dentistry [3]. In this regard, sustainability in Dentistry covers several areas, which are those of public oral health management through the implementation of primary and secondary prevention measures [4], management of public and private health care facilities dedicated to the delivery of care with the study of strategies to reduce their environmental impact [5] and home oral hygiene of patients through the evaluation of tools and materials used in this context [6]. Regarding the latter scenario, it is important to note that the manual toothbrush is universally used as the most useful tool for maintaining oral health worldwide [7]. However, the use of toothbrushes poses two environmental problems, one upstream and one downstream in their life cycle. In particular, it is indeed interesting to point out how disposable toothbrushes are mainly made of thermoplastic materials: nylon for the bristles and polypropylene-based plastic for the handle [8]. They are non-biodegradable materials (Theoretically, plastics are biodegradable, but this takes such a long time that they are considered non-biodegradable), at risk of remaining dispersed in the environment for generations and adding to the 350 million metric tons of plastic waste per year [9]. In addition, plastics, besides the issue related to their disposal and possible dispersion in the environment, also pose another problem, this time upstream in the supply chain, related to the extraction of fossil-based raw materials. 93% of plastics are made from fossil raw materials, and in 2019, generated 1.8 billion tons of greenhouse gas [GHG) emissions, accounting for about 4% of global emissions, 90% of which came from production and conversion from fossil fuels. These figures could get even worse, given that, it is estimated that by 2060, emissions from the life cycle of plastics are set to more than double to 4.3 billion tons of GHG emissions [10].

In Italy, considering the average weight of a toothbrush, which is about 17 g, about 3700 tons of plastic waste from toothbrushes are produced each year, equivalent to 150 thousand one-and-a-half-liter plastic bottles [11]. Currently, there are no precise European data on annual toothbrush consumption, but globally, 3.5 billion toothbrushes are consumed annually [12]. U.S. market data show that about 1 billion toothbrushes end up in incinerators or landfills each year (equal to 22,700 tons), and considering their combined length, they could go around the world four times. A toothbrush is thus an indispensable tool, but the product's characteristics and directions for use make it a tool that is not exactly without threats to the environment. The manual toothbrush could be considered on par with disposable plastic, given that its use is indispensable, and its replacement, to ensure its clinical effectiveness, must be constant over time [8]. According to World Health Organization (WHO) guidelines, the manual toothbrush for its action to remain effective should be changed every 3–4 months, depending on the material and type of bristles that are losing their effectiveness due to wear and tear [13]. This means that each person should use at least four toothbrushes per year, which equates, at least in Italy, to a consumption of 200 million toothbrushes annually that then could end up in landfills. In this context, there are also the important impacts upstream of the production cycle, linked to the extraction of fossil-derived material, which could make the environmental effects even worse, such as greenhouse gas emissions, which in 2022 reached a record 417.9 ± 0.2 ppb CO_2, 1923.2 ± 2 ppb CH_4 and 335.8 ± 0.1 ppb N_2O (+ 150%, + 264% and + 124%, respectively compared to 1750 levels) [14]. Therefore, in light of these considerations, it is important to find solutions that can balance proper daily hygiene and environmental sustainability. These solutions include, for example, using materials that are as sustainable as possible, such as trying to reduce the use of plastics used to make up toothbrushes and optimal end-of-life management. [15]. Therefore, in light of the above, the purpose of this study was to evaluate the sustainability of different materials used for manual toothbrush bristles, namely *nylon*, which is widely used in oral care, and *silicone*. The former, synthesized in 1935, is a polyamide fiber formed from linear macromolecules that have a recurrence of amide bonds in the chain, at least 85% of which are joined to aliphatic or cycloaliphatic groups (Fig. 1). Nylon has certain characteristics such as excellent wear resistance, good heat fastness, high elastic recovery and ease of dyeing [16].

Silicone polymers, on the other hand, are characterized by two basic groups very strong Si–O bonds (higher than C–O bonds) (Fig. 1), which provide chemical inertness, temperature, and UV resistance, and flexible organic chains formed by alkyl functional groups, which confer flexibility, low viscosity, remarkable resistance to temperature, chemical attack and oxidation, and elasticity [16].

Therefore, the two research questions were:

- Q1: What would be the most optimal solution to reduce the environmental impact of toothbrushes?
- Q2: How would the environmental impact change if only the brush head was changed instead of the whole toothbrush?

To answer the first question, Life Cycle Assessment (LCA) (ISO 14040:2006; ISO 14044:2006) [17, 18] was used, comparing different toothbrushes with different materials (silicone and nylon). To answer the second question, two

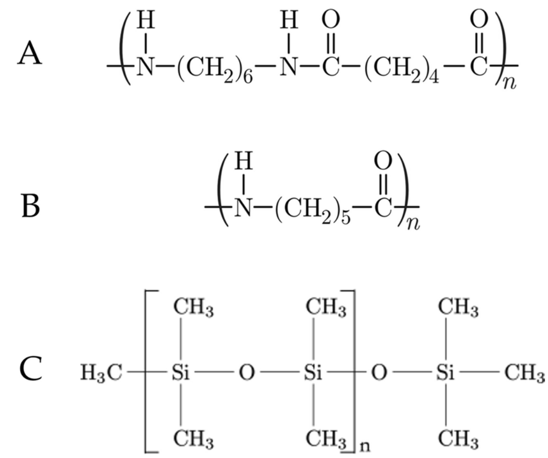

Fig. 1 Molecular structure of nylon 6.6 (**A**), nylon 6 (**B**) and silicone (**C**)

scenarios were created: a first scenario (S1) in which the entire toothbrush is discarded, and a second scenario (S2) in which instead only the interchangeable brush head is discarded, while the handle is retained, to quantify the emissions that would be avoided. For this assessment, the Carbon Footprint (CF) [19] was used, which refers to the International Panel on Climate Change guidelines and indicates in kg CO_2 eq the total greenhouse gas (GHG) emissions directly or indirectly associated with the service. SimaPro 9.5 software (PRé Sustainability, 2023) [20] was used for both assessments. To the authors' knowledge, there is only one published paper related to the sustainability assessment of toothbrushes at the state of the art [21]. The present study focuses on the sustainability of materials and assumes that the clinical efficacy of silicone and nylon bristles overlap. In fact, toothbrushes are medical devices and, as such, must undergo in-vitro and in-vivo testing to demonstrate safety and clinical efficacy prior to marketing.

Therefore, this paper could help to expand the literature on the subject and broaden the knowledge base related to the sustainability of materials in tooth care.

2 Materials and methods

For the impact assessment, six toothbrushes were considered.

- Four manual toothbrushes with Nylon bristles, a polypropylene handle, and silicone parts (N1, N2, N3, N4). N1: Elmex Sensitive Toothbrush, (Colgate-Palmolive, USA); N2: Mentadent, hard bristles, (Unilever, Netherlands); N3: Forhans Double Action Anti-Plaque Toothbrush (Forhans Original LTD, UK); N4: Sensodyne Toothbrush Sensitive, (Haleon, UK).
- Two manual toothbrushes, both with silicone bristles, but one with polypropylene handle only (Si1), the other with polypropylene handle and silicone parts (Si2). Si1: GELDIS Toothbrush, (GELDIS, Italy) Si2: GANER, A84 Toothbrush (GANER, China).

To identify and evaluate the component materials, each toothbrush was disassembled using a cutter, and each part (bristles, silicone parts, polypropylene handle) was separated and weighed using a Sartorius analytical scale. The brands and manufacturers of toothbrushes were anonymized. The materials and weights of the 6 toothbrushes assessed (Four manual toothbrushes with Nylon bristles, and a polypropylene handle and silicone parts (N1, N2, N3, N4) and Two manual toothbrushes, both with silicone bristles, but one with polypropylene handle only (Si1), the other with polypropylene handle and silicone parts (Si2) are shown in Table 1.

2.1 Life cycle assessment

Then an LCA was carried out, according to ISO 14040:2006 (Environmental Management—Life Cycle Assessment—Principles and Framework) [17, 18] and ISO 14044:2006 (Environmental Management—Life Cycle Assessment—Requirements and Guidelines) [17, 18]. The four phases were followed: (1) Goal and scope definition; (2) Life Cycle Inventory (LCI); (3) Life Cycle Impact Assessment (LCIA) (4) Interpretation.

Table 1 The weight (g) and materials of the toothbrushes considered

Parts	Materials	Toothbrushes					
		N1	N2	N3	N4	Si1	Si2
Handle	Polypropylene	12.19	10.87	9.62	12.38	10.48	11.95
	Silicon	3.74	5.48	0.88	–	–	2.29
Bristles	Nylon	0.53	0.55	0.8	0.74	–	–
	Silicon	–	–	–	–	0.52	1.03
	Steel	–	0.13	0.23	–	–	–
Toothbrushes		16.46	17.03	11.54	–	11	15.27

2.1.1 Goal and scope definition

The objective of this LCA was to assess the environmental impact of toothbrush production. The production of a toothbrush was chosen as the functional unit. Regarding the system boundaries, on the other hand, a cradle-to-grave approach was chosen, starting from the production of raw materials and ending with the finished product ready to be packaged.

2.1.2 Life-cycle inventory

The manufacturers of the five toothbrushes were contacted to identify the inventory data. The data were then modeled using the SimaPro 9.5 software database (PRé Sustainability, 2023) [20]. Specifically, polypropylene, silicone, nylon, and polyurethane came from Ecoinvent v3.8 [22], a database that contains LCI data for energy production, transportation, and chemical production. Ecoinvent v3.8 contains the only data available in the LCA software package used in this study, so the data was adapted to be as consistent as possible with the scope of the study.

2.1.3 Life cycle impact assessment

The ReCiPe Midpoint (I) was used for the LCIA, through SimaPro 9.5 [20] software, by grouping the 18 impact categories into four macro areas.

1. *Atmospheric Effects*: Global Warming Potential (GWP); Stratospheric Ozone Depletion (SOD); Ionizing radiation (IR); Ozone Formation, Human Health (OFHH); Fine Particulate Matter Formation (FPMP); Ozone formation, Terrestrial ecosystems (OFTE); Terrestrial acidification Potential (TAP),
2. *Eutrophication*: Freshwater Eutrophication Potential (FEP) and Marine Eutrophication Potential (MEP),
3. *Toxicity*: Terrestrial Ecotoxicity (TEC); Freshwater Ecotoxicity (FEC); Marine Ecotoxicity (MEC); Human Carcinogenic Toxicity (HCT); Human Non-Carcinogenic Toxicity (HNCT),
4. *Abiotic Resources*: Land Use (LU); Mineral Resources Scarcity (MRS); Fossil Resources Scarcity (FRS), Water Consumption (WC).

The ReCiPe Midpoint (I) was chosen and preferred over other calculation methods such as ILCD 2011, CML 2001, or TRACI because having the availability of eighteen impact categories (compared to 16 of ILCD 2011 Midpoint, 15 of IMPACT 2002+, 11 of CML-IA Baseline, and 9 of TRACI) can provide more comprehensive, articulate, and specific results on the environmental impacts of mushroom production than other methodologies with fewer impact categories. Therefore, Recipe 2016 Midpoint could give a broader picture with a greater degree of detail on the environmental impacts of production.

2.2 Carbon footprint (CF)

Generally, toothbrushes end up in the trash and then are disposed of in landfills. For this reason, two scenarios were created, assuming that instead of the entire toothbrush being disposed of, only the toothbrush head was changed and discarded. Specifically:

1. S1: The entire toothbrush is disposed of.
2. S2: Only the brush head is disposed of.

The objective of this scenario analysis is to assess the emissions that would be avoided. For this, the Carbon Footprint (CF) was used, based on the results of the LCIA. This is a measure that expresses the GHG emissions caused by a product or process [23]. It is expressed in kilograms of CO_2 equivalent (kg of CO_2 eq), and in agreement with the Kyoto Protocol, the following gases are considered: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrocarbons, hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), and perfluorocarbons (PFCs) [19]. Because each gas has a different global warming potential, CF was calculated as in Forster and Artaxo [24] (Eq. 1).

$$\boldsymbol{CF} = \sum \boldsymbol{G}.\boldsymbol{G}_{\boldsymbol{i}} \times \boldsymbol{k}_{\boldsymbol{i}}, \tag{1}$$

where G.G.i is the amount of GHG produced and ki is the CO_2 equivalent coefficient for that gas.

3 Results

3.1 Life cycle impact assessment

The LCIA results are expressed in Table 2 and in Fig. 2, where they have been characterized and expressed as percentages.

In particular, the impact category with the highest value was placed at 100 and the others were calculated accordingly. This visualization, obtained through the SimaPro software, serves to make the results more usable especially when the impact categories have different units. Table 2 and Fig. 2 show that the two toothbrushes with the least environmental impact are Si1 and N4, while the one with the greatest impact is N2. Among them all, Si1 turns out to be by far the most sustainable toothbrush, probably because the handle is very simple and lightweight, with no additional silicone parts but a body made of polypropylene only.

On the other hand, the toothbrush with the greatest impact is N2, in eighteen out of eighteen categories compared to all the others, mainly because it has a greater weight than the others as well as a greater amount of silicone inside the handle. Taking into consideration the two extremes (Si1 and N2), it could be seen that the more sustainable toothbrush has specific characteristics: light, simple, with a polypropylene handle with no silicone parts, and the material that makes up the bristles instead. The less sustainable one, on the other hand, is heavier and has a large silicone body and nylon bristles. Taking the results, it can be seen that N2 has higher impacts than Si1 with average values of – 90%. For example, Si1 has lower values of – 90% in GWP (4.43×10^{-2} kg CO_2 eq in Si1 vs 4.33×10^{-1} kg CO_2 eq in N2) in SOD (1.33×10^{-8} kg CFC11 eq in Si1 vs 1.33×10^{-7} kg CFC11 eq in N2) and in OFTE (7.70×10^{-5} kg NOx eq in Si1 vs 7.94×10^{-4} kg NOx eq in N2) (Table 2). Or values of – 97 in FEP and LU and – 99% in WC. This is most likely due to the smaller number of materials used in the construction of the toothbrush. Next, to assess the sustainability of the bristle materials alone, the data from the toothbrushes were averaged and normalized. Specifically, the weights of the various handle materials were averaged and two toothbrushes with the same weight, but different bristles (nylon and silicone) were assumed to be considered. The results are expressed in Table 3 (data) and Fig. 3 (characterized results).

It can be seen from Table 3 and Fig. 3 that for the same weight, silicone-bristled toothbrushes are more sustainable than nylon-bristled ones in eighteen out of eighteen impact categories, on average by – 41%.

Table 2 Life Cycle Impact Assessment results (data)

Impact categories	Unit	Si1	N3	N4	Si1	N1	N2
Atmospherical effects							
GWP	kg CO_2 eq	4.43×10^{-2}	1.00×10^{-1}	7.07×10^{-2}	2.75×10^{-1}	3.11×10^{-2}	4.33×10^{-1}
SOD	kg CFC11 eq	1.33×10^{-8}	4.06×10^{-8}	2.14×10^{-8}	7.19×10^{-8}	9.39×10^{-8}	1.30×10^{-7}
IR	kBq Co-60 eq	3.98×10^{-5}	3.46×10^{-4}	2.21×10^{-4}	1.22×10^{-3}	1.37×10^{-3}	1.98×10^{-3}
OFHH	kg NOx eq	7.27×10^{-5}	1.76×10^{-4}	1.22×10^{-4}	4.93×10^{-4}	5.58×10^{-4}	7.79×10^{-4}
FPMP	kg $PM_{2.5}$ eq	8.07×10^{-6}	6.03×10^{-5}	3.81×10^{-5}	2.09×10^{-4}	2.35×10^{-4}	3.40×10^{-4}
OFTE	kg NOx eq	7.70×10^{-5}	1.82×10^{-4}	1.26×10^{-4}	5.03×10^{-4}	5.70×10^{-4}	7.94×10^{-4}
TAP	kg SO_2 eq	9.30×10^{-5}	2.46×10^{-4}	1.67×10^{-4}	7.07×10^{-4}	8.01×10^{-4}	1.13×10^{-3}
Eutrophication							
FEP	kg P eq	6.20×10^{-7}	3.41×10^{-6}	2.21×10^{-6}	1.15×10^{-5}	1.29×10^{-5}	1.85×10^{-5}
MEP	kg N eq	2.94×10^{-7}	9.64×10^{-7}	6.38×10^{-7}	1.25×10^{-6}	1.76×10^{-6}	2.35×10^{-6}
Toxicity							
TEC	kg 1,4-DCB	1.09×10^{-2}	2.28×10^{-2}	1.76×10^{-2}	6.21×10^{-2}	6.93×10^{-2}	9.53×10^{-2}
FEC		1.29×10^{-5}	3.71×10^{-5}	2.31×10^{-5}	9.39×10^{-5}	1.09×10^{-4}	1.51×10^{-4}
MEC		8.23×10^{-6}	2.29×10^{-5}	1.52×10^{-5}	6.09×10^{-5}	6.95×10^{-5}	9.66×10^{-5}
HCT		2.80×10^{-6}	7.87×10^{-6}	5.12×10^{-6}	2.25×10^{-5}	2.56×10^{-5}	3.61×10^{-5}
HNCT		2.09×10^{-4}	5.23×10^{-4}	3.90×10^{-4}	1.53×10^{-3}	1.71×10^{-3}	2.38×10^{-3}
Abiotic resources							
LU	m^2a crop eq	6.74×10^{-4}	4.19×10^{-3}	2.75×10^{-3}	1.44×10^{-2}	1.61×10^{-2}	2.32×10^{-2}
MRS	kg Cu eq	4.95×10^{-5}	8.45×10^{-5}	6.69×10^{-5}	1.97×10^{-4}	2.21×10^{-4}	2.94×10^{-4}
FRS	kg oil eq	2.28×10^{-2}	3.26×10^{-2}	2.73×10^{-2}	7.48×10^{-2}	8.32×10^{-2}	1.09×10^{-1}
WC	m^3	3.43×10^{-4}	6.09×10^{-3}	3.66×10^{-3}	2.21×10^{-2}	2.49×10^{-2}	3.63×10^{-2}

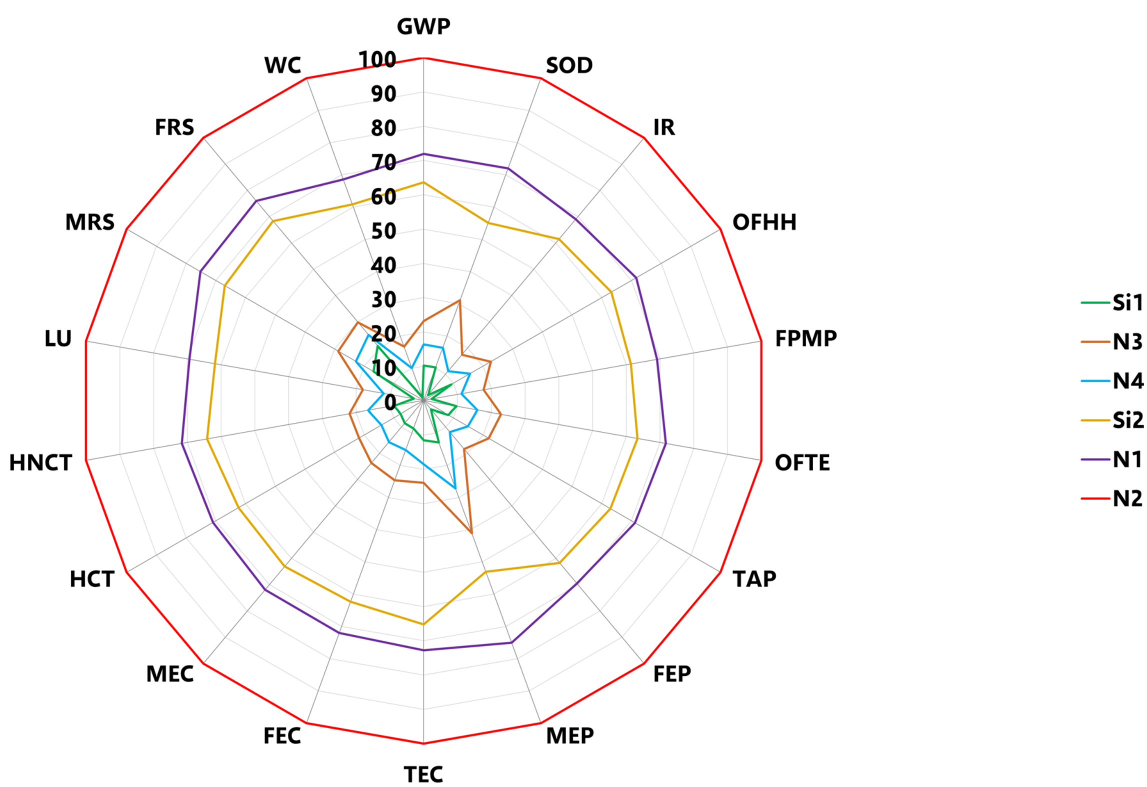

Fig. 2 Life cycle impact assessment results (characterized results)

Table 3 Sustainability comparison between toothbrushes with Nylon bristles and toothbrushes with Silicone bristles (data)

Impact categories	Unit	Toothbrushes with silicon bristles	Toothbrushes with nylon bristles
Atmospherical effects			
GWP	kg CO_2 eq	4.32×10^{-1}	2.54×10^{-1}
SOD	kg CFC11 eq	1.19×10^{-7}	7.96×10^{-8}
IR	kBq Co-60 eq	2.03×10^{-3}	1.13×10^{-3}
OFHH	kg NOx eq	7.79×10^{-4}	4.56×10^{-4}
FPMP	kg PM2.5 eq	3.47×10^{-4}	1.93×10^{-4}
OFTE	kg NOx eq	7.94×10^{-4}	4.66×10^{-4}
TAP	kg SO_2 eq	1.13×10^{-3}	6.56×10^{-4}
Eutrophication			
FEP	kg P eq	1.89×10^{-5}	1.06×10^{-5}
MEP	kg N eq	1.99×10^{-6}	1.49×10^{-6}
Toxicity			
TEC	kg 1,4-DCB	9.54×10^{-2}	5.60×10^{-2}
FEC	kg 1,4-DCB	1.49×10^{-4}	8.65×10^{-5}
MEC	kg 1,4-DCB	9.62×10^{-5}	5.57×10^{-5}
HCT	kg 1,4-DCB	3.61×10^{-5}	2.10×10^{-5}
HNCT	kg 1,4-DCB	2.40×10^{-3}	1.39×10^{-3}
Abiotic resources			
LU	m2a crop eq	2.37×10^{-2}	1.32×10^{-2}
MRS	kg Cu eq	2.89×10^{-4}	1.75×10^{-4}
FRS	kg oil eq	1.07×10^{-1}	6.68×10^{-2}
WC	m^3	3.71×10^{-2}	2.05×10^{-2}

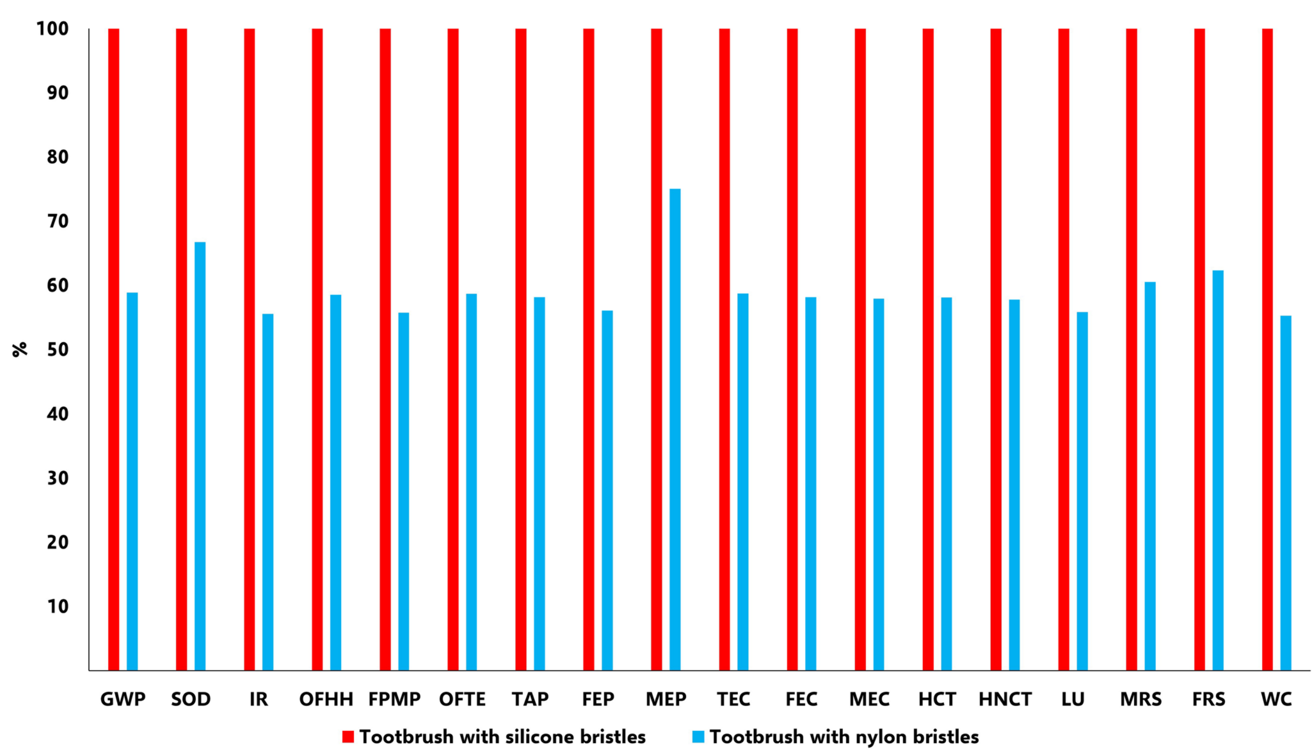

Fig. 3 Sustainability comparison between toothbrushes with Nylon bristles and toothbrushes with Silicone bristles (data)

3.1.1 Carbon footprint

The CF results show that in S1, i.e., disposing of the entire toothbrush in a landfill, the environmental impact is 5.02×10^{-3} kg CO_2 eq, while in S2, i.e., disposing only the brush head and keeping the handle, it is 3.34×10^{-4} kg CO_2 eq (Fig. 4). Therefore, the emission savings of this "strategy" is 4.69 10^{-3} kg CO_2 eq.

4 Discussion

The toothbrush with silicone bristles and a polypropylene handle (Si1) is the best option among those taken into consideration, according to the LCA results, while the toothbrush with nylon bristles and a polypropylene handle with silicone inserts (N2) is the worst option. Si1 has a better environmental profile because of its silicone bristles combined with a lightweight, straightforward handle and a polypropylene body that lacks any additional silicone components. N2, on the other hand, had more weight than the others and a handle with more silicone in addition to nylon bristles. Nylon, while having important qualities such as high impact and wear resistance, good abrasion and aging resistance, and hygroscopicity, has a very energy-intensive production process and requires high amounts of electricity, natural gas, and fuel oil, as also demonstrated by Sim and Prabhu [25].

Furthermore, as a polyamide fiber, it is produced by spinning polymers that are derived from the reaction between an acid and a chemical element, such as hexamethylenediamine, a petroleum derivative [26]. This in fact, again also considering the higher weight and greater amount of material used, is reflected, for example, in a higher GWP for N2 of 4.33×10^{-1}, which is higher than for all other brushes considered (10 times compared to Si1, 4 times compared to N3, 6 times compared to N4, 1.5 times compared to Si2, and 1.39 times compared to N1). In general, however, among the various chemical production processes, the plastics industry stands out for producing a significant amount of waste and pollutants. In particular, the polyamide industry, which also includes nylon 6 and nylon 66, generates a significant production of byproducts due to low selectivity in the cyclohexane oxidation reaction, such as oils containing n-pentanol, cyclohexanone, and cyclohexenes [27]. These, if dispersed in the environment, can be toxic to both ecosystems and humans, with effects related to skin, eye, and respiratory tract irritation, headaches and dizziness, dyspnea and coughing,

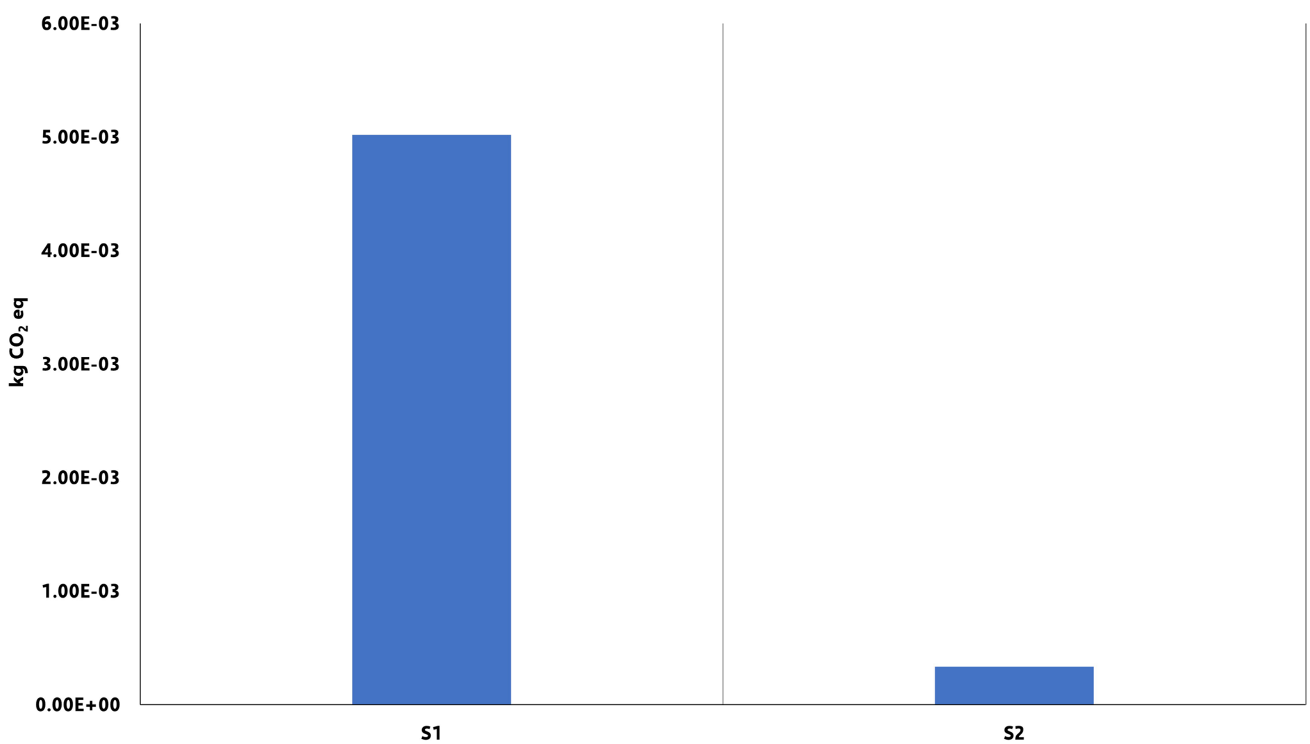

Fig. 4 Carbon Footprint for the two scenarios: S1 = The entire toothbrush is thrown into the landfill; S2 = Only one interchangeable head is thrown into the landfill

etc. This is especially evident in the toxicity-related impact categories, such as HCT and HNCT, where the N2 toothbrush outperforms the other toothbrushes considered by values that are 13 to 2 times and 11 to 2 times, respectively. For instance, N2 shows values of 3.61×10^{-5} kg 1.4-DCB in the case of HCT, which is 13 times higher than the more sustainable option Si1, or 2.38×10^{-3} kg 1.4-DCB in the case of HNCT. On the other hand, silicones can boast interesting properties that make them practical for repeated use over time: they have high elasticity at low temperatures and good resistance at high temperatures, are washable, flexible, strongly water-repellent, and are within a certain limit of malleable and deformable. In addition, the results show that it is a more sustainable material than Nylon, and indeed, the Si1 toothbrush shows better environmental performance than other Nylon toothbrushes in all impact categories considered, with % impact reductions ranging from – 96% to – 100%, again also taking into account lower weight. In fact, unlike plastics, it does not contain petroleum, lead, PVC, or substances that are potentially harmful to both human health and ecosystems [28]. In addition, compared to some types of plastics, silicone is fully recyclable [29, 30], addition to the fact that it does not require petroleum-based materials but comes from silicon, which is the second most abundant element in the Earth's crust (27.7% by mass) [31] thus limiting issues related to its scarcity. For example, compared to the less sustainable Nylon counterpart (N2), it shows GWP values of −96% (4.43×10^{-2} kg CO_2 eq vs 4.33×10^{-1} kg CO_2 eq), as well as values of – 100% in the remaining atmospheric categories (e.g., 7.27×10^{-5} kg NOx eq vs 7.79×10^{-4} kg NOx for OFHH or 8.07×10^{-6} kg $PM_{2.5}$ eq vs 3.40×10^{-4} kg $PM_{2.5}$ eq for FPMF, and so on). The LCA results, therefore, show that between the two materials, at the level of sustainability, the one preferable for bristles is silicone over nylon. Regarding the assessment of impacts downstream of the production cycle, the CF showed that the best case scenario would be in S1, i.e., disposing of the entire toothbrush in a landfill, the environmental impact was 5.02×10^{-3} kg CO_2 eq, while in S2, i.e., disposing only the brush head and keeping the handle, it was 3.34×10^{-4} kg CO_2 eq. Therefore, the emission savings of this "strategy" was 4.69×10^{-3} kg CO_2 eq. Open landfills are known to receive a large amount of plastic waste from the industrial and domestic sectors, as well as sludge from wastewater treatment plants. After being placed in landfills, plastic wastes undergo a series of physicochemical and biological transformations, resulting in highly contaminated wastewater, called leachate. Within them, personal care products can incorporate microplastics [31]. Furthermore, once thrown into landfills, plastics undergo initial aerobic biodegradation and then switch to anaerobic conditions [32], with the subsequent influence of acid formation and methane fermentation from organic solid waste [33]. Even in the absence of light and oxygen, landfilled plastics continue to fragment into microplastics primarily due to fluctuations in temperature (60–95 °C) and pH (4.5–9), fire, physical stress, and (although limited) microbial activity [34]. Therefore, by reducing the number of toothbrushes within the landfills and thus discarding only the brush head instead of the entire toothbrush, it is shown how the share of total waste could be reduced and thus indirectly have a reduction in the amount of total greenhouse gases.

The most commonly used toothbrush is the one with nylon bristles, followed by the one with silicone bristles. There are also alternatives defined for advertising and marketing purposes as green, and these are the toothbrushes with bamboo handles and nylon bristles. While there are many studies on the efficacy of the first two models after use, there is a lack of such evidence for those with bamboo handles. Furthermore, it should be noted that since the brush head is not detachable from the handle, the entire toothbrush is thrown into unsorted waste at the end of use [11]. Finally, the current research centers on the sustainability of materials, operating under the assumption that both silicone and nylon bristles exhibit comparable clinical efficacy. Given that toothbrushes are categorized as medical devices, they are required to undergo both *in-vitro* and *in-vivo* testing to establish their safety and clinical effectiveness before being marketed.

5 Conclusions

This study aimed to evaluate the sustainability of the materials used for manual toothbrushes and to identify, through LCA and CF, what could be the elements that would minimize their environmental impact. The results showed that to improve the sustainability of manual toothbrushes, future research should focus on (i) eliminating unnecessary material; (ii) developing lighter-weight models; and (iii) developing models where only the brush head is replaced. The ideal toothbrush must be lightweight, reduce the amount of superfluous material, and use less impactful resources, with evidence-based proven efficacy in biofilm disruption.

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the conception and critically revised the manuscript. Andrea Scrascia contributed to the conception of the manuscript. Laura Gobbi contributed to the design and analysis of the manuscript. Giuliana Vinci contributed to data interpretation and critically revised the manuscript. All authors gave their final approval and agreed to be accountable for all aspects of the work.

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Declarations

Competing interests The authors declare no conflict of interest.

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