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The environmental consequences of oral healthcare provision by the dental team

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ABSTRACT

Objectives: To undertake a comparative ecological impact (Total lifetime carbon footprint and single use plastics (SUP) waste generation) derived from the provision of professional oral healthcare (Dentists and hygienist) to five different patient categories up to the age of 50 years, representative of different levels of progressive dental disease and treatment experience.

Method: CO_2e and SUP waste generated was calculated for five patient categories with common preventable diseases; that are representative of different levels of progressive dental disease and treatment experience. The assessment is based on the average restorative care levels for 50-year-olds in the UK. The number of appointments for each procedure was calculated using current evidence-based guidelines. The total lifetime carbon and the SUP waste analysis was calculated using published peer-reviewed data.

Results: The total carbon footprint follows a progression with low impacts for individual persons with very low disease and treatment experience (285 $KgCO_2e$), escalating to very high impacts (approximately 2,170 $KgCO_2e$) for people with high levels of disease and treatment experience. SUP waste follows a similar linear rise across the different cohorts of dental experience over a lifetime (6–50 years), from 1,382 items and 4.6 Kg for patients in a the very low dental experience, to 12,200 items and 33.8 Kg for patients in the cohort of very high dental experience.

Conclusions: The provision of all oral healthcare carries an environmental impact in the form of carbon footprint and SUP waste. The cumulative lifetime environmental impact of oral healthcare is proportional to the disease and treatment experience of the individual person for these preventable diseases; with a x8 difference between the two extremes of experience.

Clinical Significance: All forms of oral healthcare have an environmental impact. The most effective way to mitigate these impacts is through the promotion and provision of effective evidence-based preventive oral healthcare.

1. Introduction

Climate change and environmental pollution represent two of the greatest challenges facing humanity and the planet. The energy requirements and waste produced from the provision of oral healthcare has a direct and profound impact on these environmental challenges. The greatest contribution to the oral healthcare carbon footprint comes from patient travel and staff commute. In England, this has been estimated to account for about 60% of the total greenhouse gas emissions from NHS dental services (2013 to 2014), measured 675,706 tonnes of CO_2e [1]. This is the equivalent of 211,000 flights from the UK to Hong Kong (250 kg CO_2e per passenger per hour flying in a Boeing 747 – 400 × 13 hrs) [2]. A carbon dioxide equivalent or CO_2 equivalent (CO2e) is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential [3].

With regards to waste, a conservative estimate of the plastic waste (single use plastic) generated from the direct provision of oral healthcare treatment in a dental practice in the UK, is estimated to be 2.4 bn SUP items (27 tonnes) per annum; not accounting for the waste from the upstream supply chain [4]. The oral healthcare profession is a highly wasteful economy that largely operates in a linear supply chain, with little recycling and energy recovery. Currently the Minamata convention

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is the only international legislation that directly addresses environmental concerns in oral healthcare, but is limited to the release of Hg [5].

From a mitigation perspective, there is wide recognition that the most effective and preferable way to limit environmental impacts is through a reduction of energy use and waste production, as depicted in the respective hierarchy strategies (Fig 1) [6,7]. A reduction of 'need' for dental treatment translates into a reduction in energy use and waste production. In oral health, the best approach to achieve this, is by targeting the need for treatment of preventable oral conditions and diseases with environmentally sustainable impacts across the whole of the supply chain.

Dental caries, periodontal diseases, tooth loss and oral cancers are largely preventable and can be treated in their early stages [8]. These oral diseases affect close to 3.5 billion people worldwide, making it the most dominant conditions that affect humanity for over 30 years [9,10].

The promotion and achievement of good oral healthcare will result in reduced demand for necessary disease management treatments that use high levels of energy and produce much waste [11]. Recycling remains a challenge at the patient end-user level; but less so with packaging and uncontaminated SUPs. Most of the contaminated biomedical waste impact lies downstream of the supply chain with the oral healthcare professionals, patients and end-user consumers. This waste problem is further compounded by the increased use of personal protective equipment (PPE) [12].

The arising hypothesis is that the prevention of 'preventable' oral diseases results in fewer interventions, which bring benefits to the individual, society, national economies and as an unintended consequence, it has environmental benefits [11]. Whilst this relationship is highly plausible, it remains as an empirical concept that has not been proven with a quantifiable cause and effect relationship. This study seeks to provide the evidence to support the hypothesis that good oral healthcare with prevention at its core, has a reduced environmental impact, compared to unmanaged progressive oral disease. The aim of this study is to undertake a comparative ecological impact assessment (total lifetime carbon footprint and SUP waste generation) of five patient categories, representative of different levels of progressive dental experienced between the ages of six to fifty years of age. This study focuses on the environmental impacts derived from the provision of professional oral healthcare (Dentists and hygienist).

2. Method

CO_2e and waste generated in the form of single use plastics (SUP) was calculated for five patients, that are representative of different levels of progressive dental experience. The assessment is based on the average restorative care levels for 50-year-olds in the UK. Primary disease and treatment incidences were obtained from the UK Adult Dental Health Survey 2009 (ADHS 2009) [13]. The number of appointments for each procedure was calculated using current evidence-based guidelines: NICE Recall Guidelines [14], BSP Guidelines [15], FGDP Radiography Guidelines [16] and Delivering Better Oral Health [17]. The total lifetime carbon footprint was derived by multiplying the number of appointments over the lifetime (6–50 years) by the carbon footprint (CO2e) for each procedure, derived from the published literature [1]. SUP waste analysis was calculated in a similar manner, using published data [4].

The methodology used in this study is divided into four sections that are combined to provide the required interpretation of results:

1. Dental Experience.
2. Categorisation of dental experience.
3. Carbon footprint
4. Assumptions and limitations

2.1. *Dental experience (Disease and treatment)*

We defined the different levels of dental experience in the UK for the age cohort of 50 years of age. The mean oral healthcare of a 50-year-old person in the UK was calculated using data from the ADHS 2009, with a focus on the age category 45–54 (Table 1). This was considered to be representative of a life time of dental experience and associated care. The following three categories were used as indicators of disease experience:

1. Number of extracted and missing teeth
2. Periodontal condition
3. Number of sound and untreated teeth

2.1.1. *Number of extracted and missing teeth*

The number of extracted and missing teeth was calculated from table 11.1.3 in the ADHS 2009 (Appendix):

- Number of natural teeth: 26.1
- The upper bound that includes third molar teeth, is 32–26.1= 5.9 teeth.
- The lower bound that excludes third molar teeth, is 28–26.1=1.9 teeth.

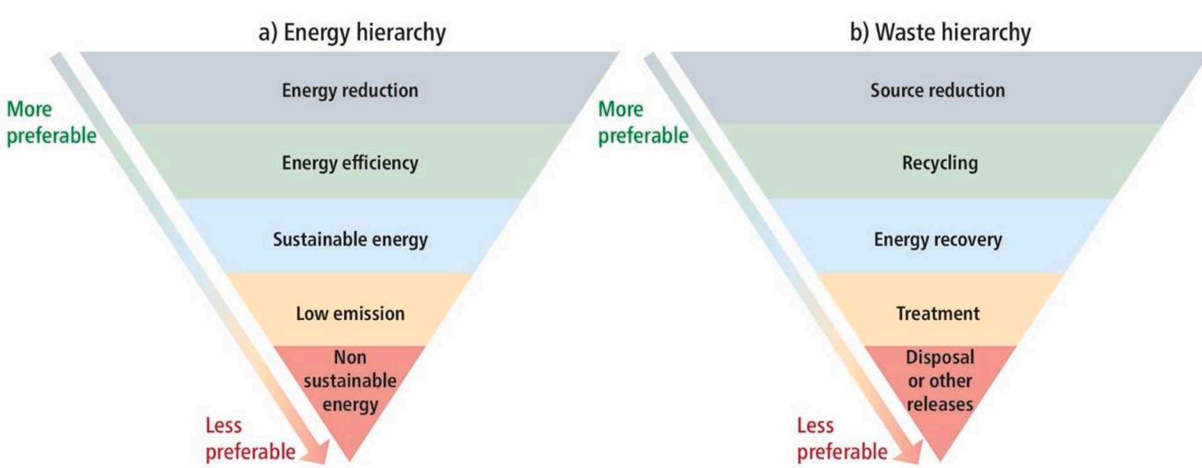

Fig. 1. Inverted pyramids for energy and waste hierarchies. First published in 'SDG 7: affordable and clean energy in oral healthcare' British Dental Journal, Vol 235, 454–455, 2023 by Springer Nature.

Table 1
Oral health and disease/treatment experience for a 50-year-old in the UK. The mean level of disease, calculated from the ADHS 2009, is labelled as a 'High' and the zero values as 'Very low' assuming some elements of preventive non-operative care (i). From this point, the levels for the 'Low', 'Moderate' and 'Very High' categories have been extrapolated. For ease of international interpretation, the periodontal status uses adjectives (good, moderate, severe) mapped to the EFP classification of periodontal disease (ii). 'Treated teeth' include teeth that were subsequently extracted. 'Extracted teeth' include teeth that were previously treated.

Dental experience (Disease and treatment) Estimated Disease Status	**Periodontal Status (ii)**	**Treated teeth**	**Extracted teeth**
Very Low (i)	Excellent(Periodontal Health)	**0**	**0**
Low	Good(Localised Gingivitis)	5	0
Moderate	Moderate(Generalised Gingivitis)	10	1
High (i)	**Mild-moderate Periodontitis** (Code III Periodontitis)	**15**	**4**
Very High	Severe Periodontal disease(Code IV Periodontitis)	20	8

- An average of these values equals 4 teeth extracted or missing (excluding third molars)

2.1.2. Periodontal condition

The periodontal condition by characteristics of dentate adults, was calculated from table 11.2.10 in the ADHS 2009 (Appendix):

The mean periodontal condition was identified between gingivitis and periodontitis with mean pocket depths of 4mm.

2.1.3. Number of sound and untreated teeth

The number of sound and untreated teeth by characteristics of dentate adults, was calculated from table 1.2.3 in the ADHS 2009 (Appendix):

- The average patient had 15.1 sound and untreated teeth.
- The number of restored and treated teeth are obtained by subtracting from the full dentition:
  - The upper bound that includes third molar teeth, is 32–15.1 = 16.9 restored and treated teeth.
  - The lower bound that excludes third molar teeth is 28–15.1 = 12.9 restored and treated teeth.
  - An average of these values equals 15 restored and teeth.
  - The opposite value of this, was taken as the mean for sound and untreated teeth, that equals a mean of 15 teeth
- There was no identifiable age-related data in the literature for the mean number of root-canal treated teeth or teeth with direct or indirect restorations according to age groups.
- There was also no identifiable data for repeat RCT and/or the replacement and repair rate of direct and indirect restorations.

2.2. Categorisation of oral health and disease and treatment experience

The derived 'dental experience' data was used to categorise oral health, disease and treatment experience for individuals (Table 1). The calculated level of previous dental experience has been labelled as 'High' and the zero values have been set for the category of 'very low' assuming some preventive non-operative care. From this point, the levels of 'low', 'moderate' and 'very high' have been extrapolated. These categories are depicted in the illustrations shown in Fig. 2. Clinical approximations of these categories are shown in Fig. 3. Periodontal experience is classified in a generic manner, that bridges the 2020 EFP classification for periodontal disease and the 2009 ADHS incidence data that precedes the use of the EFP classification and terminology [18].

2.2.1. Maintenance recall intervals

The recall interval for the different oral health maintenance procedures was based on current evidence-based guidelines, detailed in Table 2. The frequency of interventions and the number of appointments per procedure for each of the dental disease experience categories from the age of 6 to the age of 50 years in the UK is shown in Table 3.

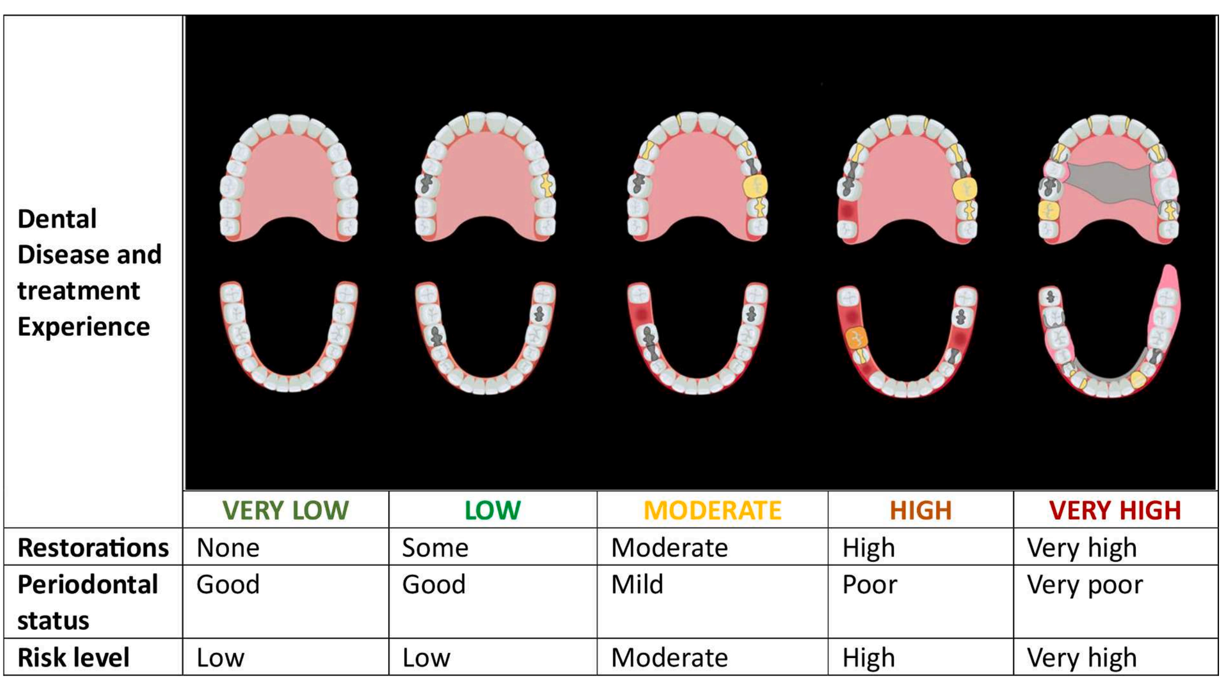

Fig. 2. Diagrammatic representation of the previous levels of dental disease and treatment experience, mapped to Table 1.

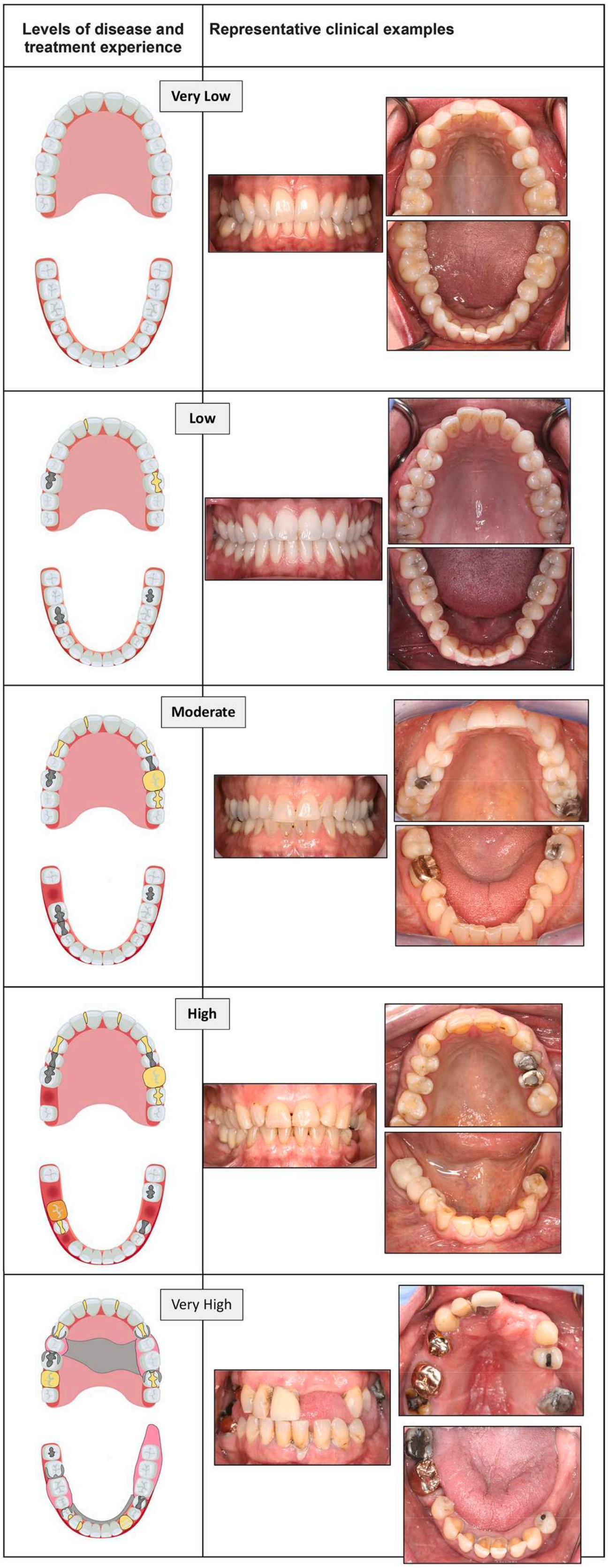

Fig. 3. *Column 1:* Diagrammatic representation of the different levels of disease and treatment experience identified in Table 1 and depicted in Fig. 2. *Column 2:* Representative clinical examples of previous levels of previous dental disease and treatment experience.

Table 2
UK Guidelines used to determine the maintenance recall intervals.

Evidence-based Guideline	Recommendations Used
NICE Recall Guidelines [14]	• <18yrs - max interval should be 12 months (3,6,9,12 possible) • >18years - max interval should be 24 months (3,6,9,12,15,18,21 possible)
BSP Periodontal Guidelines [15]	• Code 4: Full periodontal charting of all sextants. PMPR to begin. • 9–12month recall period for stable periodontitis • 6 monthly recall common • 3 monthly PMPR is the shortest interval recommended.
FGDP Selection Criteria for Dental Radiography [16]	<u>Caries Screening (permanent dentition)</u> Bitewings (one right, one left) • High caries risk: 6 monthly BWs • Moderate caries risk: 12 monthly bitewings • Low caries risk: 24 monthly bitewings <u>Periodontal Radiographs</u> • Code 3: horizontal BWs, supplemented by PAs of anterior if feel valuable • Code 4: >6 mm pocketing. PAs/vertical BWs. • OPT may be justified if also heavily restored dentition. • Need yearly rads to monitor PDD. <u>Endodontic Radiographs</u> • Preoperative essential (with pre-exam appointment) • Working length radiograph (with endo treatment appt) • Cone fit (with endo treatment appt) • Post-op (with endo treatment appt) • Follow up one year after completion (at review examination appt)
Delivering Better Oral Health [17]	Fluoride varnish Age / Low risk / High risk 6–18 / ×2 yearly / > ×2 yearly >18 / – / ×2 yearly

2.3. *Carbon footprint and SUPs*

2.3.1. *Analysis of carbon footprint*

The number of appointments for each procedure for the 44 years (6 to 50 years of age) for each patient category was calculated using current evidence-based guidelines. The total lifetime carbon footprint was subsequently calculated by multiplying the number interventions per procedure times the carbon footprint per procedure as per the published data from Public Health England [18].

The calculation was based on an estimated fourteen different patient appointments per day. This accounted for one clinician return (there and back) journey per day and fourteen patient return journeys. Patient travel was included for all main patient-attendance procedures and excluded for procedures that would routinely be provided as part of (secondary to) a main patient-attendance procedure (see assumptions). In this manner, the 'Total impact carbon footprint' per main procedure per category (disease and dental experience) was calculated.

2.3.1.1. Carbon footprint conversions. For ease of interpretation and

Table 3
Calculation of the frequency of interventions and the number of appointments per procedure for each of the dental disease experience categories from the age of 6 to the age of 50 years in the UK. See the 'Assumptions section' for clarification and interpretation of the data.

Procedure	**Disease and Treatment Experience** **Very Low**		**Low**		**Moderate**		**High**		**Very High**	
	Freq of intervention	**Number of appointments**	**Frequency of intervention**	**Number of appointments**	**Frequency of intervention**	**Number of appointments**	**Frequency of intervention**	**Number of appointments**	**Frequency of intervention**	**Number of appointments**
Examination	6y to18y= =Every 6 m	12m×2=**24**	6y to18y = =Every 6 m	12m×2=**24**	6y to18y = =Every 6m	12m×2=**24**	6y to18y = =Every 6m	12m×2=**24**	6y to18y==Every 3m	12m×4=**48**
	18y to 50y = =Every 24m	32m÷12=**16**	18y to 50y = =Every 24m	32m÷12=**16**	18y to 30y = =Every 18m	144m÷18=**8**	18y to 30y = =Every 12m	240÷12=**20**	18y to 30y== Every 6m	144m÷6=**24**
					30y to 50y = Every 12m	240m÷12=**20**	30y to 50y = Every 9m	240m÷9=**27**	30y to 50y==Every 3m	240m÷3=**80**
Total		**40**		**40**		**52**		**63**		**152**
Radiographs	Bitewings 6y to 50y= =Every 24m	528m÷24=**22**	Bitewings 6y to 50y==Every 24m	528m÷24=**22**	Bitewings 6y to 30y==Every 24m	24m÷2=12	Bitewings 6y to 18y==Every 24m	144m÷24=**6**	Bitewings 6y to 18y==Every 12m	144m÷12=**12**
							Bitewings 18y to 30y = =Every 12m	216m÷12=**18**	Bitewings 18y to 50y= =Every 6m	64m×6=**30**
					Bitewings 30y to 50y = =Every 12m	240÷12=**20**	Bitewings 30y to 50y = =Every 9m	240m÷9=**27**		
					RCT= 5 PAs	2RCT×5PAs=**10**	RCT=5 PAs Extractions= =1PA	3RCT×5PAs=**15** 3 Extractions×1PA= =**3**PAs	RCT=5 PAs Extractions==1PA	6RCT×5 PAs=**30** 8 Extractions×1PA= =**8**PAs
							Periodontal==2 DPT (cancelled out with recall BWs)	0	Periodontal code1–3=BWs Periodontal code 4= =OPT/Pas (in place of BWs) 28y to 50y= =DPT every 12 m (replace BWs)	22y×DPT=**22** DPT
Total		**22**		**22**		**42**		**69**		**114**
Periodontal Treatment (Non-surgical)	Supra PMPR 18y to 50y= =Every 24m	32m÷2=**16**	Supra PMPR 18y to 50y= =Every 24m	32m÷2=**16**	Supra PMPR18y to 30y= =Every 18m	144m÷18=**8**	Supra PMPR18y to 30y= =Every 12m	144m÷12=**12**	Supra PMPR18y to 22y = Every 12m	48÷12=**4**
					Supra PMPR 30y to 50y= =Every 12m	240m÷12=**20**	Supra PMPR 30y to 36y= =Every 6m	72m÷6=**12**	Supra PMPR 22y to 28y=Every 6m	72m÷6=**12**
							Sub PMPR 36y to 50y Initial treatment=2 Followed by one year= =2×sub PMPR every 4m=8	Initial 2+8=**10**	Sub PMPR 28y to 50y Initial treatment= =2 Followed by one year= =2×sub PMPR every 4m=8	Initial 2+8=**10**
							36y to 50y Maintenance=Every 6 m continuous	156÷6=**26**	29y to 50y Maintenance = Every 6 m continuous	252 m ÷ 6 = **42**
Total		**16**		**16**		**28**		**86**		**110**

(*continued on next page*)

Table 3 (*continued*)

Procedure	Disease and Treatment Experience Very Low		Low		Moderate		High		Very High	
	Freq of intervention	Number of appointments	Frequency of intervention	Number of appointments	Frequency of intervention	Number of appointments	Frequency of intervention	Number of appointments	Frequency of intervention	Number of appointments
Fluoride Varnish	6y to18y= =Every 6 m (At the same appt as the examination)	240m÷12=**20**	6y to18y = =Every 6 m (At the same appt as the examination)	240m÷12=**20**	6y to18y = =Every 6m	240m÷12=**20**	6y to18y= =Every 6m	240m÷6=**40**	6y to 18y= =Every 3m	240m÷3=**80**
	–	–	–	–	–	–	18y to 30y= =Every 12m 30y to 50y= =Every 9m	144m÷12=12 240m÷9=**27**	18y to 50y= =Every 6m	384m÷2=**64**
Total		**20**		**20**		**20**		**79**		**144**
Direct placement Restorations	–	Restorations=0	–	RBC=2 Replacements=0	–	Visible=5 Replacements=**2** Prior to crown placement=2×2 teeth=**4** – Amalgam:6 RBC:4 GIC:1	–	Visible=11 Replacements=**1** Prior to crown placement=2×3 teeth=**6** (×2) restorations in (×4) extracted teeth= =**8** Amalgam=10 RBC=12 GIC=2	–	Visible=4 Replacements=**11** Prior to crown placement=2×6 teeth=**12** (×2) restorations in (×7) extracted teeth=14 Amalgam=15 RBC=16 GIC=3
Total		**0**		**2**		**11**		**26**		**34**
Indirect Placement Restorations		Restorations=0		Restorations=0	Precious metal=1 Ceramic=1	Visible=2	Precious metal=1 Ceramic=2	Visible=3	Precious metal= =3 Non-precious metal=1 Non-precious metal on extracted teeth=2	Visible=4 One previously on x2 extracted teeth=2
Total		**0**		**0**		**2**		**3**		**6**
Root Canal Treatment		0		0		RCT on teeth with crowns (assumption)=2		RCT on teeth with crowns (assumption)=3		RCT on teeth with crowns (assumption)=6
Total		**0**		**0**		**2**		**3**		**6**
Impressions for Study Casts		0		0	Impressions for casts per crows =1	2 crowns=2	Impressions for casts per crown=1	3×crowns=3	Impressions for casts per crown=1 Impressions for casts per RPD=2	6×crowns=6 1×RPDs=2
Total		**0**		**0**		**2**		**3**		**8**
Extraction of teeth							Extractions=4	**4**	Extractions=9	**9**
Total		**0**		**0**		**0**		**4**		**9**
Removable Part Dent		**0**		**0**		**0**		**0**		**4**
Total		**0**		**0**		**0**		**0**		**1**
Cumulative Total		**102**		**104**		**162**		**245**		**547**

Table 4
Total number of separate patient appointments that require generic SUP items. Based on published data [4]. See the assumptions section for clarification and interpretation of the data.

Level of disease experience	Separate patient appointments that require generic SUP items
Very Low	40 (exam appointments)
Low	42 (exam appointments plus 2 restoration appointments)
Moderate	52 exams appts plus 11 restoration appts plus 2 indirect (4 appointments), 2× RCT (4 appointments) =71
High	63 exam appts, 74 Hygiene appts, 24 restorations, 3 indirect (6 appts), 3 RCT (6 appts), 4 extraction appts=177 appointments
Very High	152 exam appointments, 106 periodontal appointments, 34 restorations, 6 indirect (12 v), 6 RCT (12 appts), 9 extractions, 1 RPD (5 appointments) =330

meaningfulness, the carbon footprint values are converted into reader-friendly comparisons: Sea ice lost, passenger aeroplane flights, car journeys, trees to be planted.

2.3.1.2. Car journeys. The CO_2 emissions per car journey are derived using the published data from the UK Department for Transport CO_2 emissions factor for an average petrol car which is 0.180 kg CO_2 /vehicle km and the average loading for a car is 1.6 people/journey [19].

Car emissions 0.1125 kg CO_2e per person/km

Calculation: Carbon footprint/0.1125

2.3.1.3. Passenger airplane flights. Emissions from a standard commercial aircraft are derived using published data for a Boeing 737–400 [20].

Boeing 737–400: 115 g CO_2/passenger km

Calculation:

- Carbon footprint in kg × 1000 = carbon footprint in grams (g)
- Carbon footprint in g/115 = number of km

2.3.1.4. Number of trees necessary to absorb CO_2 emissions. The number of trees that need to be planted to absorb the CO_2 emissions are derived using published data for the amount of CO_2 absorbed by trees and other vegetation [21]

Calculation: A tree of 10 years of age can absorb up to 21.8 kgCO_2/year.

Calculation: Carbon footprint/21.8

2.3.1.5. Sea ice lost. The amount of sea ice lost from anthropogenic CO_2 emissions is derived using the published data [22].

- 3 m^2 of sea ice lost per 1000 kg of CO_2.
- Calculation: Carbon footprint/1000×3

2.4. Analysis of Single Use Plastic

The number and mass of Single Use Plastics (SUPs) per procedure and per appointment was calculated from the published data [4]. This data includes all the common procedures (Dental examinations, periodontal treatment, endodontic treatment, direct placement restorations, prosthodontic - fixed & removable, oral surgery treatment. The data source accounts for both generic items used all the time and for those specific to each dental procedure (Table 4). Further calculations were derived for radiographs and fluoride varnish.

2.5. Assumptions & limitations

A number of assumptions are made to conduct this study, that are based on best consensual judgement of current practice and reasonable approaches. The specific assumptions may lead to either under or over-estimations, that are explained. These assumptions are applied to the whole data set and as such, they do not impact on the overall comparative assessment of the different categories. Specific assumptions for each dental experience category are listed in Table 5.

2.5.1. General assumptions

- Analysis of the data is based on current guidelines, applied to the patient's oral healthcare throughout their entire life between the ages of 6 and 50.
- The caries risk level is same throughout life of the individual. This is not realistic as it can fluctuate in relation to life customs and social influences. This leads to an underestimation as it fails to consider risk peaks.
- Prevention measures (as per ADHS) are likely not in place throughout the patients' lives. A person that has been treated throughout lifetime with regular prevention measures is assumed to have better oral health status and therefore a lower carbon footprint associated with treatment needs.
- Dentists are more likely to replace and re-restore for a number of iterations prior to the placement of a full coverage crown. This leads to an earlier entry of the restorative cycle creating overestimates.
- Dentists will often combine several procedures into one appointment. We have made the assumption that procedures were provided independently at every appointment. This will lead to an overall overestimation.

2.5.2. Dental experience assumptions

- All patients age 50 years old.
- Dental experience under 6 years old is not considered as we have established this as the boundary between primary and secondary dentition. Moreover, there is very limited data for this age cohort, that would require incorrect assumptions creating a bias of the adult data set.
- All appointments from the age of 6 (the start of the permanent dentition) were included
- All patients have been registered with a dentist age 6–50 and are regular attenders.

2.5.3. Categorisation of dental experience

- All calculations made according to current treatment and recall intervals guidelines.
- Patients attended all appointments at the stipulated recall intervals.
- All missing teeth have been extracted.
- Sedation or general anaesthetic (GA) is seldom required and therefore not included.
- No patient appointments were cancelled or missed

2.5.4. Procedure specific assumptions

- No fissure sealants were placed. We did not include the DBOH recommendation for 'Fissure sealant' procedures, as this is a procedure that is undertaken very erratically in dental practice. This will lead to an under-estimation error for the high and very high categories.
- Direct placement restorations have been placed twice: The original restoration and a subsequent replacement restoration.

Table 5
Specific assumptions for the different levels of dental experience.

Level of Disease and Dental Experience	Assumptions
Very Low and Low	**Low disease risk status.** • Assume with examination appointments: Scale and Polish, Radiographs, Fluoride Varnish (as per DBOH) [17]
Moderate	**Moderate disease risk status.** • Assume with examination appointments: Scale and Polish, fluoride varnish and baseline radiographs • Radiographs for root canal treatment procedures are completed at treatment appointments and examinations.
High	**High disease risk status.** • Assume with examination appointments: Baseline and periodontal bone level radiographs, scale and polish age 18–30, fluoride varnish. • Endodontic radiographs taken at treatment appointments. • Assume attendance to the hygienist: From age 30–50 the patient attends separate appointments with a dental hygienist. • Assume patient develops periodontal disease at age 36. • Fluoride varnish application: 2x yearly for 18+ patients at all examination appointments with dentist.
Very High	**Very high disease risk status.** • Assume provided at time of examination appointments: baseline and periodontal radiographs, scale and polish age 18–22, fluoride varnish. • Assume treatment with hygienist: from age 22–50 patient attends separate appointments with a dental hygienist. • Assume patient develops periodontal disease at age 28. Fluoride varnish is also completed with a hygienist.

- All the crowned teeth have been previously restored and root-canal treated, and therefore all radiographs required for crown provision, had been previously taken for the root-canal treatment.
- Multi-step procedures are were completed in the minimum number of appointments.
- For diagnostic study casts. One appointment is required for each indirect restoration and two appointments for RPD provision.
- The management of periodontal conditions under 18 years of age is excluded.
- Once a patient is diagnosed with periodontal disease, the following assumptions are made:
  - Patients with low and very low disease incidence, undergo supragingival PMPR (if required) at the examination appointment by the dentist. This is calculated as a travel-excluded procedure.
  - Patients with unstable periodontal disease are stabilised after two initial root surface debridement (Sub-gingival PMPR) interventions. This is to be followed with 3 monthly maintenance reviews for up to one year. We then assume that the disease status stabilises and the patient only requires two appointments for RSD (PMPR) every 6 months for maintenance. These treatment interventions are considered to be procedure-specific appointments and are calculated as travel-included procedures. This applies to the moderate, high and very high disease and dental experience categories.
- Removable partial denture provision is considered to be a six-appointment process. The first two for primary and definitive impressions are accounted for in other appointments (study casts). Four appointments are considered for the provision of an RPD.
- Fixed, tooth-supported bridges (fixed partial dentures) are not included, due to the absence of data for this item.
- All the extractions, direct and indirect restorations, RPDs and endodontic treatments were completed at independent appointments

2.5.5. Carbon footprint and SUP waste assumptions

Limitations arise from the use of the PHE carbon footprint data that makes its own limitations and assumptions as reported in the publication. This relates to 2014 and may not be fully representative of the current status, considered to be an underestimate.

- A dentist sees 14 patients a day.
- A travel excluded value is used for the following additional procedures that are undertaken at the same time as another principal procedure: Radiographs, fluoride varnish and impressions for study casts.
- For the purposes of use and extrapolation of the PHSE data, that accounts only for Scale and Polish (S&P) procedures, Root Surface Debridement (RSD) is grouped with S&P. There is an acceptance that this is an inaccuracy as local anaesthesia is often required for RSD (Sub-gingival PMPR).
- Radiographs, supragingival PMPR (done by the dentist), fluoride varnish and study casts are exclusive of patient travel. The assumption is that these interventions take place at the same appointment as a main patient-attendance procedure.
- Travel calculations for specific procedures were based on the following assumptions: Two appointments per root canal procedure; two appointments per indirect procedure (e.g., crown, bridge) and; five appointments per removable partial denture.
- The environmental impact (carbon footprint and SUPs) arising from additional treatment procedures (e.g., extractions under N_20, IV sedation, surgical removal of third molars, orthodontic treatment, periodontal surgery, implants) are not included. These procedures do not take place on a regular basis and that they have a significant adverse impact.

3. Results

The total lifetime environmental impact for the different levels of patient experience is represented as a function of carbon footprint and SUP usage (Table 6; Figs. 4, 5 and 6).

The total lifetime carbon footprint can be represented in a more meaningful manner as lost sea ice, passenger aeroplane flights, car journeys and trees to be planted (Table 7). The SUP usage (number and mass of items) is expressed as a function of building bricks and bags of flour (Table 8)

4. Discussion

There is a general recognition that the provision of effective oral health, with a focus on prevention, leads to reduced environmental impacts in the form of CO_2e and SUP waste [12]. Oral healthcare professionals have a responsibility to provide sustainable oral healthcare that does not compromise the future generations of our patients or our planet.

This paper quantifies the cumulative lifetime environmental impact that arises from professional oral healthcare provision (dentist and hygienist), as a function of a progressive range of lifetime of oral healthcare experiences, for people between the ages of 6 to 50 years. The method used disease epidemiological data from the UK population (Wales, England and Northern Ireland, excluding Scotland) using incidence of disease from the Adult Dental Health Survey 2009 [13] and environmental impacts for different treatment modalities from the published literature. As such, the findings are representative of this geographical region. There is recognition that there are clear variations in the data across the different world regions. However, the disease patterns and treatment modalities are considered to be representative of the different stages of disease and treatment status of human oral health on a global basis; enabling effective extrapolation of the findings across all regions.

This study focuses on oral health conditions and diseases that are considered to be preventable and as such it excludes developmental conditions. Also, it does not consider some aspects of dental care that may be considered to be an elective procedure, usually driven by a desire to improve or correct a real or perceived aesthetic problem. This type of treatment decision may lead to the provision of an irreversible operative treatment intervention for teeth which are healthy and symptomless. For similar reasons, orthodontic treatment was excluded from this study as it is considered a non-routine procedure and as such not applicable to the whole population. Tooth extractions are undertaken either at the end point of the restorative cycle [24], with an associated large accumulated environmental impact or as elective procedures (orthodontic or third molars) with a lesser impact. The calculations in this study are based on the worst-case scenario, assuming a high restorative burden prior to the eventual and inevitable extraction.

All forms of oral healthcare have an environmental impact. In this study we have assessed this over the lifetime of a person up to the age of 50. The total carbon footprint follows a non-linear progression with low impacts for people in the 'very low and low' disease and treatment experience (285 and 302 Kg CO_2e, respectively), with a significant escalation to the next grouping of moderate to very high, reaching an impact of approximately 2170 KgCO_2e for people with very high levels of disease and treatment experience. This represents a difference of x8 between the two extremes. The trend for the use of SUPs across the different cohorts of dental experience follows a very similar trend. There is a non-linear rise in the use of SUPs over a lifetime (6–50 years), with a marked step up for the moderate to very high categories, within an overall range from 1382 items and 4.6 kg for patients in a the very low dental experience, to 12,200 items and 33.8 kg for patients in the cohort of very high dental experience. Single use plastics are an indispensable technology that is used across all healthcare settings with an increasing prevalence in oral healthcare. They are found in packaging, devices and products, including personal protective equipment (PPE); that has further increased its usage during the COVID pandemic and re-affirmed its use as an essential tool in healthcare cross-infection control. The impact from these cohorts can be extrapolated to the whole world population of eight billion, highlighting in equal measures, the environmental benefits resulting from the promotion and provision of good preventive oral healthcare and the dramatic consequences to the

Table 6
Total lifetime environmental impact from the different levels of dental experience as a function of carbon footprint and SUP waste.

Level of previous dental experience	Environmental Impact		
	Total carbon footprint (kg CO_2e)	Total SUP items by:	
		Number	Weight (g)
Very Low	285	1382	4576
Low	302	1488	4664
Moderate	610	2801	9021
High	1209	7129	21,877
Very High	2170	12,191	33,787

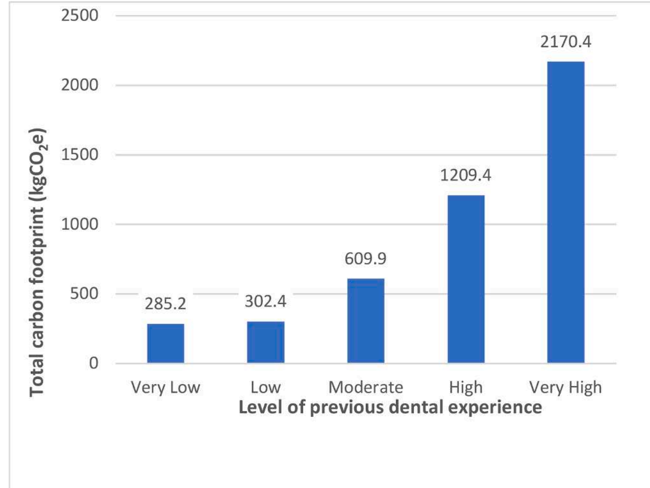

Fig. 4. Total carbon footprint from patients with different levels of previous dental disease and treatment experience.

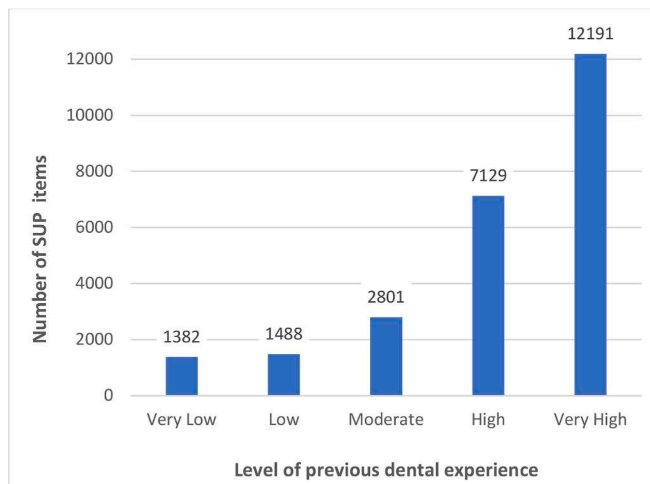

Fig. 5. Total number of Single Use Plastics (SUPs) used for treatment in patients with different levels of previous dental disease and treatment experience.

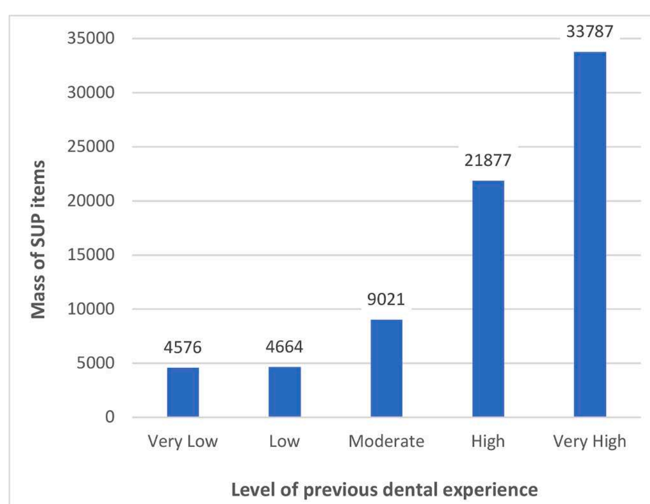

Fig. 6. Total weight of Single Use Plastics (SUPs) used for treatment in patients with different levels of previous dental disease and treatment experience.

Table 7
Summary of carbon footprint for the various levels of dental experience.

Level of previous dental experience	Total carbon footprint (kg CO_2e)	Distance in car per person (Approx.)	Distance travelled by passenger plane per person	Number of mature tree years required to offset the emissions	Area of sea ice lost
Very Low	285	2533.3 Km *Paris to Moscow*	2478.3 Km	13.1	0.9 m^2
Low	302	2684.4 Km *Paris to Ankara*	2626.1 Km	13.9	0.9 m^2
Moderate	610	5422.2 Km *Paris to Dubai*	5304.3 Km	28	1.8 m^2
High	1209	10,746.6 Km *Paris to Singapore*	10,513 Km	55.5	3.6 m^2
Very High	2170	19,288.8 Km *Paris to Hong-Kong (x2 journeys)*	18,869.6 Km	99.5	6.5 m^2

Table 8
Summary of SUP usage for the different levels of dental experience.

Level of previous dental experience	Number of SUP items	Weight of SUP (g)	Weight in bricks [23] (2600 g)	Bags of flour (1500 g average)
Very Low	1382	4576	1.7	3.05
Low	1488	4664	1.79	3.11
Moderate	2801	9021	3.46	6.01
High	7129	21,877	8.41	14.58
Very High	12,191	33,787	12.95	22.52

environment from a failure to do so.

The analysis of the data is based on current guidelines, applied to the patient's oral healthcare throughout their entire life between the ages of 6 and 50. This may cause an overestimation of the carbon footprint as a function of the assumed treatment appointments (e.g., High disease risk patients have low attendance rates REF) or an underestimation as a result of the high levels of dental treatment required for neglected and failing dentitions. Also, a significant number of assumptions were made in this study, based on the available data and healthcare guidance documents, that will influence the actual results for each patient cohort. The assumptions are applied universally to the whole data set for all the patient cohorts. As a result, whilst the actual figures can be considered as effective estimations, the proportionality between the different patient cohorts remains unaffected enabling effective comparisons to be made. This confirms the hypothesis that the provision of oral healthcare has an environmental impact with an upward trend that is proportional to the disease and treatment experience of the individual. Thus, the take home message 'that the pursuit, achievement and maintenance of oral health, through preventive programmes and good quality care is the most effective route to environmental sustainability' is affirmed [11,12]. The promotion and achievement of good oral health that prevents oral diseases will result in improved population health, economic benefits and as an unintended consequence, there will be a reduced demand for interventive operative treatments that use high levels of energy and produce much waste.

There is a recognition that as well as the environmental impact from professional care, as explored in this study, each disease risk patient cohort has an additional environmental impact that is directly attributable to their personal oral hygiene regime. We may work on the assumption of an inversely proportional correlation between disease risk and personal engagement with oral hygiene regimes. Consequently, this generalisation would suggest that a patient identified in this study as 'low disease risk', will probably engage in higher levels of personal preventive oral hygiene regimes than someone in a 'high disease risk' category. These additional environmental impacts are derived from the use of oral hygiene home-care protocols that include cleaning aids (tooth brushes, interproximal brushes, floss), dentifrice, water and energy consumption. It is difficult to quantify the impact of personal preventive regimes as we currently lack this data in a comprehensive study. A simplified extrapolation of the environmental impact from the implementation of a recommended OH home-care regime over the 44-year period (6–50 years of age), brushing twice per day with a pea-sized amount of dentifrice, would suggest this to be: 264 tubes (75 ml) [25] + 132 manual toothbrushes (replaced every 4 months) + 19,272 litres of water (600 ml [26] × twice per day) plus the unaccounted energy used in manufacturing, distribution and waste disposal. Notwithstanding, it is important to note that the multiple environmental impacts derived from poor oral health significantly outweigh the cumulative (home + professional) impacts of good oral health. This point identifies and confirms that all activities have an environmental impact with a significant increase when interventive operative care is required.

Additionally, careful consideration should also be given to the environmental impact of elective procedures. The impact arises from the intervention itself, the associated maintenance and any need for revisions or replacements that may take a low-risk patient into an unavoidable iterative restoration-placement and replacement cycle. Equally, we must also be conscious that patients and their caring clinicians should not be burdened with 'environmental anxiety' and under duress to avoid procedures that are required, for the management of diseases and conditions with health, functional or psychological benefits. The results from this study should not be misinterpreted and that patients do not feel that going to the dentist is bad for the environment. The provision of oral healthcare should be considered in the context that every human activity has an environmental impact. We need to manage this impact and the most effective way to do this in oral healthcare, is to pursue an evidence-based preventive programme under the guidance of oral healthcare professionals. Wherever possible, patients should engage with their oral healthcare as co-creators and co-managers in collaboration and under the professional guidance of their oral healthcare professional. The converse is true, that failure to engage with professional-driven preventive care may be deleterious to oral health leading to increased treatment interventions and will result in a greater environmental impact.

The link between good oral healthcare and reduced environmental impacts lies in the concept of reduction. This is a well-established and powerful operational strategy used by the energy sector and the United Nations Environment Programme [5,6,27]. These two hierarchical strategies provide a very effective framework for our sector. We can mitigate our carbon footprint and waste production across the whole of the supply chain, from manufacturer to the clinics, by reducing the amount of treatment for conditions that are largely preventable. The central tenent of this reduction strategy is effective management of patient care, with risk-focused, patient-centred prevention and supported by good quality practice that will jointly lead to reduced treatment need and optimised durability of treatment. The concept of prevention is widely accepted as the most effective way of managing diseases and the societal pressures that arise from this, including inequalities. Disease prevention is a relatively simple concept, that appears to be extremely challenging to implement in a universal manner. Key to success, is an understanding and management of disease risk factors, so that personal decisions can directly mitigate disease incidence and the associated environmental impacts.

At the point of delivery of care, *reduction* is achieved through the provision of good oral healthcare by engaging with good practice, as detailed in the four domains [11]: *Preventive care, Operative care, Integrated care*, and *Ownership of care.*

- Preventive care – The assessment and management of systemic and local risk factors with a practical and patient-centred preventive regime.
- Operative care – The combination of core knowledge, skill sets, experiential learning, and team work acting synergistically. The provision of high-quality operative interventions results in durable treatment that will require fewer repairs and replacements.
- Integrated care – The integration of services and appointments, patient-centred structured treatments and patient participation as co-creators and co-managers of their care.
- Ownership of care – Active participation in core and complementary activities that leads to professional development, a passion to excel and the satisfaction of achievement.

The actual number of physical dental appointments and patient travel can be further reduced through careful management of family appointments, matched to risk levels; together with the use of effective digital information systems, such as telemedicine and remote clinical consultations [28–30].

5. Conclusions

The provision of oral healthcare carries an environmental impact in the form of carbon footprint and SUP waste. The prevention of 'preventable' oral diseases results in fewer interventions, which bring benefits to the individual, society, national economies and environmental benefits.

This study provides the evidence to support the hypothesis that good oral healthcare with prevention at its core, has a reduced environmental impact, compared to unmanaged progressive oral disease.

The cumulative lifetime environmental impact of oral health, that arises from the provision (or lack of) professional care (Dentists and hygienist), is proportional to the disease and treatment experience of the individual person. The lowest environmental impacts are associated with low disease risk, activity and low treatment experience to approximately x9 higher impact for a high disease risk, activity and treatment experience.

The most effective way to reduce the environmental impact of oral health is through a reduction of the need to treat preventable diseases. An effective preventive regime is the best way to ensure good oral healthcare that requires reduced patient travel together with minimal interventive and maintenance treatment with reduced environmental impacts as an unintended consequence.

Research data

The data used to calculate the total environmental impacts (Carbon footprint and Single Waste Plastics) that supports this research publication has been shared – This data can be freely downloaded from the University of Sheffield Research Data Repository at https://doi.org/10.15131/shef.data.24996509, under the terms of the Creative Commons Attribution (CC BY-NC 4.0) licence.

CRediT authorship contribution statement

Nicolas Martin: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Abigail Hunter:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Zoe Constantine:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Steven Mulligan:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors whose names are listed immediately below certify that they have NO conflict of interest with the subject matter or material described and discussed in this manuscript. Nicolas Martin, Abigail Hunter, Zoe Constantine, Steven Mulligan. School of Clinical Dentistry, Claremont Crescent, University of Sheffield S10 2TA

Supplementary materials

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