Manuscript without author details
Click here to view linked References

Environmental impacts from conventional and digital dental crown fabrication workflows: A comparative life cycle assessment

Introduction

The fabrication processes for indirect prosthetic dental restorations (manufactured outside the oral cavity) are in a period of transition with three main approaches currently used: conventional, digital and mixed hybrid workflows. Increasingly, there is a drive towards digital and hybrid workflows, as they provide greater speed, versatility of fabrication and predictability of outcomes. Although digital workflows are consistently regarded as being more environmentally sustainable [1–5], there is a lack of objective data that determines their environmental impact. This work aims to address this knowledge gap by undertaking a comparative Life Cycle Assessment. Today, informed clinical treatment decision-making must consider environmental impacts and ways to mitigate them. There is a need to establish a knowledge baseline that identifies the true environmental impacts arising from these workflows and the hotspots within the workflows that contribute most significantly. For context, bespoke indirect restorations (e.g. dental crowns) are fabricated using specific materials (polymer, metal, ceramic or a combination of these) to replace tooth structure, and/or teeth with consideration to the functional and aesthetic needs of the prosthesis [6–8]. A workflow for the fabrication of a dental prosthesis consists of four distinct sequential stages: 3D intraoral data acquisition (physical or digital) -> design of the prosthesis -> fabrication -> fitting in the mouth/tooth. An additional step for the provision of an interim restoration would normally be required when the fabrication takes place in a dental technology laboratory.

A workflow with conventional fabrication technologies uses physical intra-oral impressions and technological fabrications that include casting (investment, centrifugal and pressure die), porcelain densification by sintering (PFM crowns), fusion of porcelain to non-precious metals, polymerisation of acrylics and resin-based composites, soldering and welding; all of which require high levels of specialist technical skills. The physical intraoral impressions are transported to a dental technology laboratory to create a replica gypsum cast of the dentition for which the restoration is fabricated. This workflow is unidirectional and requires multi-step procedures and in the event of error, a return to the early stages of the workflow. Conventional fabrication techniques require additional clinical occlusal data and often the mechanical articulation of the casts.

An alternative digital workflow uses intraoral digital scans and CAD-CAM fabrication that enable the use of alternative materials with improved properties (9). Three-dimensional intraoral data acquisition of the tooth preparation or implant fixture is the essential preliminary step to provide an accurate replica that will enable the subsequent fabrication of the dental prosthesis. Intraoral scanners create instant accurate and high resolution three-dimensional topographical digital replicas of the dentition in the form of a standard tessellation language (STL) file. Highly sophisticated specialist software is used to design an optimised restoration that includes the required occlusal considerations. The digital restoration STL file resulting from the CAD (Computer Aided Design) informs the advanced CAM (Computer Aided Manufacturing) fabrication process (additive or subtractive). Additive fabrication technologies used in dentistry include 3D printing, stereo photolithography (polymer casts) and laser sintering (non-precious metal alloys). Subtractive technologies are analogous, with computer-aided milling used for grinding a block of material (polymer, ceramic or metal) into the predetermined restoration shape [10–13]. The milling units can be scaled in size to enable milling of a single restoration (clinical chairside) or multiple batch-milling as used in dental technology laboratories. A hybrid, intermediate approach uses, either a 3D scan from a gypsum cast to create a digital file [6–9]

or sends an intra-oral scan (IOS) to a technical laboratory that will print a 3D plastic model on which the crown is manufactured; thereafter these pathways follow the digital fabrication workflow process.

All fabrication workflows carry inherent environmental impacts. These are mostly anecdotal subjective perceptions that need to be substantiated through empirical research (Table 1). To date, no studies have assessed the environmental impacts from these different workflows. In any workflow there are 'hotspots', that relate to areas or processes that are particularly inefficient or in this case, pose higher environmental impacts. These may be associated with material use, the equipment itself, the use of energy-intensive processes, waste generation or transportation, for example. A pinch analysis identifies these points and the opportunities to mitigate their impact through focused solutions, such as energy recovery, optimisation of technology use, effective recycling of obsolete equipment or waste material. In this context, a cradle-to-grave Life Cycle Assessment (LCA) provides the ideal tool for this task - A comprehensive method for evaluating the environmental impact of a product, process, or service throughout its entire life cycle, from raw material extraction to disposal.

The aim of this study is to undertake a comparative cradle-to-grave environmental life-cycle assessment of conventional versus digital workflows for the fabrication of a dental ceramic crown, in order to address the knowledge gap and provide quantitative analysis of the potential impact of both fabrication workflows, and to test the assumption that digital workflows result in lower environmental impact This is the first study of its kind to measure and quantify the environmental impacts of each workflow and in this way provides the required knowledge base to inform more sustainable clinical practices and guide the dental community toward adopting more environmentally responsible approaches. Though the present study necessarily includes a series of assumptions, it highlights hotspots in each process, enabling comparison and highlighting opportunities to reduce environmental impact.

Table 1: Perceived and anecdotal environmental impacts for conventional and digital workflows

	Conventional Fabrication Workflow	Digital Fabrication Workflow
Characteristics	· Multi-stage clinical and technical workflow. · Enables combination of technologies and materials (metals, ceramics and polymers) for the design and fabrication of compound devices. · Use of many different sundries and materials that require procurement, storage, use and disposal – Associated energy use and waste generation. · Correction and repetition of work often require re-start of the clinical/technical workflow. · Fabrication technologies are low-medium capital investment	· Reduced clinical and technical stages. · Enables the use of optimised materials that can only be shaped through CAD/CAM milling and grinding. · Clean, fast with the use of sophisticated technologies. · Corrective and iterative process that includes occlusal design and form optimisation. · Enables the fabrication of multiple identical prostheses at different points in time. · Fabrication technologies are medium-high capital investment

Clinical Data Acquisition (Tooth/arch impressions)	· Extensive waste generation with diverse waste streams · Need for transportation of impressions to the dental laboratory. · Need for physical occlusal articulation. · Inherent cumulative human errors that may require work repeats.	· No transportation requirement · Digital data transfer · No further intermediate steps
Design of the Prosthesis	· Casting of gypsum model and dye preparation. · Multi-stage human input leads to variable and unpredictable outputs · Remakes may require re-start of the clinical/technical workflow.	· CAD-based with highly predictable sophisticated software algorithms. · Requires the printing of a plastic 3D polymer model. · Unknown energy for server/cloud data use/storage.
Fabrication of the Prosthesis	· Limited range of materials (e.g. zirconia ceramics not possible) · Extensive range of equipment required. · High use of materials, energy and sundries. · Only one prosthesis as a workflow output	· Clinic-based CAD-CAM technology permits one-appointment restorations · Unknown and variable use of materials, energy and sundries. · Environmental impact from the technologies is unknown

Methodology

Life Cycle Assessment (LCA) is a technique used to estimate the environmental impact of a product or process. The method involves defining the materials, processes and sub-products required to produce a product, and considering the fundamental requirements of each, in terms of resource use, energy use, and environmental impacts. When applied to each sub-process and summed, the impact of the product can be ascertained. In this study, LCA was used to consider the environmental impact of conventional and digital workflows, and to consider the hotspots and areas of significance in each, both independently and through comparison.

Life cycle assessment

i. Goal and Scope

The goal of the LCA is to compare the environmental impacts of digital and conventional workflows in the manufacture and necessary procedures for provision of a dental crown. An attributional LCA was

performed according to the ISO 14040:2006 guidelines (Environmental management: Life cycle assessment, Principles and framework) for the comparison of the environmental impact of digital and conventional workflows.

A functional unit describes the amount and action of the product that will be analysed. The functional unit for this project was 'one dental crown', manufactured and ready to cement in a dental practice in the UK. Due to material density, the zirconia and lithium disilicate crowns had different mass: 3g for the zirconia crown and 2g for the lithium disilicate crown. The scope of this study is 'cradle-to-grave'. Energy consumption, device transportation, patient travel, manufacturing and waste management were included in the model. The UK context enabled the use of accurate region-specific data, improving the robustness of the results.

ii. Life Cycle Inventory

Primary data collection and material outputs required for the LCI of each process of conventional and digital workflow, were obtained from Dentsply Sirona, Degudent GmbH (Hanau, Germany). Several parameters were defined as assumptions and listed below (Table 2).

Patient transportation distances were based on the literature [15] and laboratory transportation distances were based on three different scenarios (local, national and international). Further details are given below.

Proxies were used in three specific instances where data on the specific raw materials required was not available. One such instance related to the use of potassium alginate impression material in the conventional workflow. Sodium alginate was used as a proxy for potassium alginate, following seaweed biorefinery LCA study work by Nilsson et.al [25]. Since both are alginates and have very similar properties and preparation routes, this proxy is expected to yield similar results to the intended product. In two cases, proxies were used for materials of the dental equipment: PBT (Polybutylene terephthalate) in the intraoral scanner housing, and POM (Polyoxymethylene) in the furnace. In each case, the most suitable proxy was selected by identifying materials with similar properties and production routes. Full details are given in the Life Cycle Inventory Table (Appendix 1, see Research Data). PET (Polyethylene terephthalate) is a commonly used proxy for PBT, as was the case here. The two have very similar properties and preparation methods, differing only slightly in chain length. Formaldehyde was used as a proxy for POM since POM is a polymerised version of formaldehyde, meaning the chemical composition and processing are identical prior to polymerisation. For waste scenarios, according to the data collected from the manufacturer, most of the waste goes to landfill, however recommendations are made for the owner of the intraoral scanner, milling machines, 3D-printers and furnaces to dispose of these devices according to the local regulations, which varies greatly across the world and predominantly involves landfill as the default scenario. For this LCA, two waste treatment scenarios were considered for the main study: a) mixed treatment (where some of the parts are recycled); b) sanitary landfill. Further details are given in the End-of-life treatment section, and full inventory details for each material are given in the Life Cycle Inventory table (Appendix 1, see Research Data).

iii. Life Cycle Assessment

This study used SimaPro version 9.6.0.1 (SimaPro, London, UK) as a life cycle assessment software tool and the database ecoinvent version 3.10 (ecoinvent, Zurich, Switzerland), which includes an extensive

collection of processes, some of them country specific. All the data was entered into SimaPro and assessed across eighteen environmental impact categories defined by the ReCiPe 2016 Midpoint Hierarchical impact assessment method v 1.09

iv. Sensitivity Analysis

For this life cycle assessment, assumptions were made for the distances between dental surgery and technology laboratory (device transport), patient travel, the number of daily patient appointments for the provision of a ceramic crown and the lifespan of digital machinery.

Sensitivity analysis was undertaken in two areas: End-of-life treatment scenario and laboratory transport distance. Two end-of-life treatment scenarios and three laboratory transport distances were considered.

Furthermore, a tool was designed to enable variation to inputs and assumptions to be made and the impact of this viewed directly. This tool was used to undertake further sensitivity analysis of results, and to assess the impact of assumptions, investigate the effect of proxies and consider the potential for changes in outcomes due to future developments, such as electric vehicles, grid electricity impact factor reduction, or changes in material impact.

By identifying current and hypothetical workflow hotspots, the tool enables the various stakeholders to consider future important factors in routes to decrease the carbon footprint of the fabrication of a dental ceramic crown.

v. Fabrication Workflows

The primary aim of this study is to compare the environmental impact of conventional and digital workflows in the manufacture and necessary procedures for provision of dental crowns. For each of these scenarios, a series of other variables including material options, laboratory location, and end-of-life treatment have been considered. In parallel with conventional and digital workflows, the CEREC (Chairside Economical Restoration of Esthetic Ceramics) one-time appointment has also been considered. This one-time appointment technique is designed to minimise patient inconvenience of multiple appointments and associated intermediate restorations. The different fabrication workflows and the associated inputs are diagrammatically represented in Figure 1.

Three different workflows were assessed and compared: (i) The digital workflow with landfill end-of-life treatment, (ii) the digital workflow with mixed end-of-life treatment (laboratory-based and CEREC chair-side one-time appointment scenarios), and (iii) the conventional workflow with landfill end-of-life treatment.

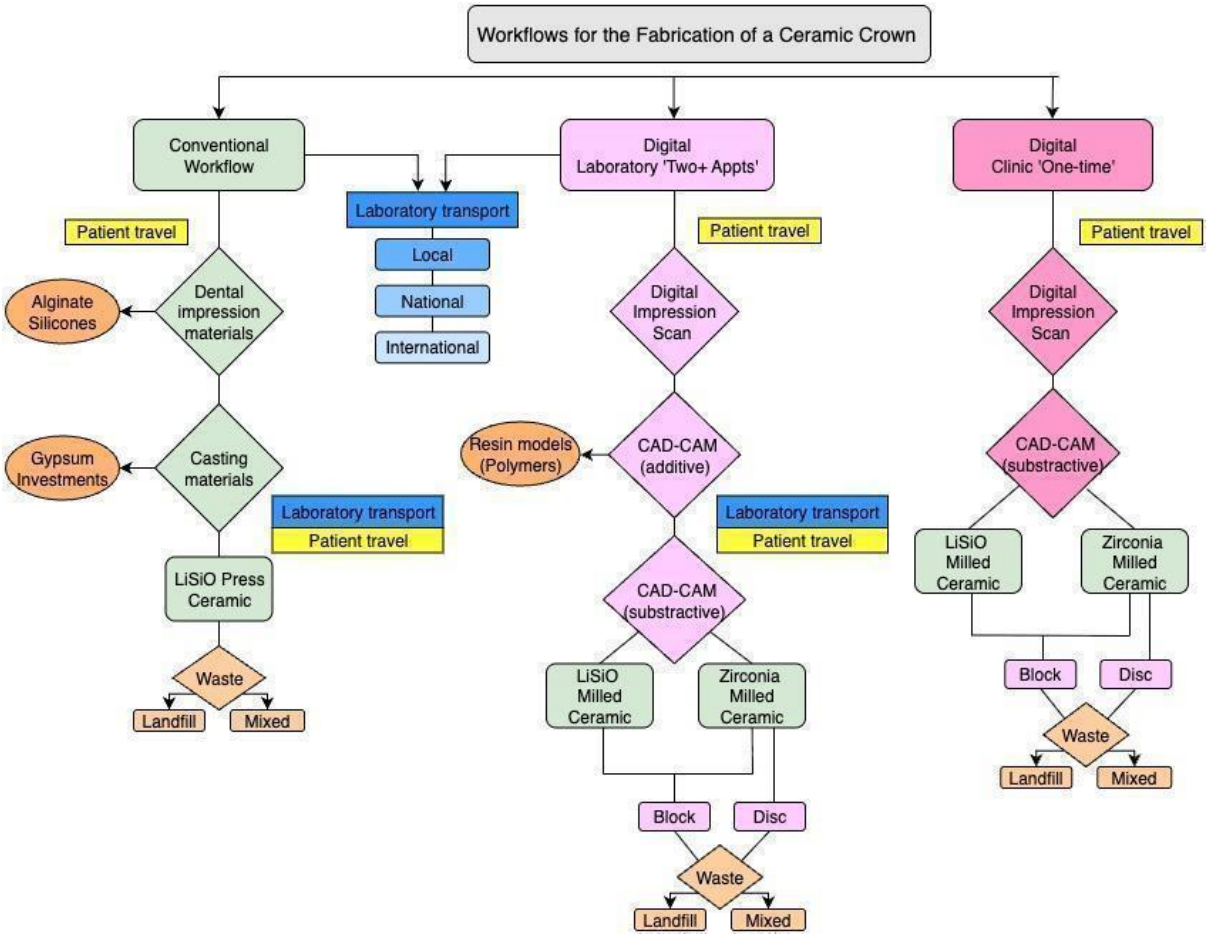


Fig 1. Conventional and digital (Laboratory-based and Clinic-based one time) workflows for the fabrication of a ceramic dental crown with lithium disilicate and zirconia. All workflows include the core and secondary use of technologies and materials with an indication of the waste streams for each.

vi. Crown material

Two ceramic material types were considered in this study: Zirconia and Lithium Disilicate. Both materials produce clinically successful restorations and are firmly established as the principal materials for the fabrication of all-ceramic crown restorations [16–19]. Zirconia was included in the digital workflow only as it requires milling a 'green state' zirconia dioxide softer blank (block or disc) that is subsequently sintered to achieve final dimension and physical properties. Lithium disilicate is used both in the conventional workflow in form of ingots of lithium disilicate ($Li_2Si_2O_5$) through a combination of lost-wax and molten pressing techniques and in the digital workflow by milling a (pre-) crystallized block finally resulting in a lithium disilicate (LS2) restoration [20]. All the materials and their proprietary names are included in the inventory within the appendices.

The dental laboratory based digital manufacturing workflow compared two formats of the zirconia disc of the same diameter but different height: 300 g mass and 460 g mass. In this case study, a standard crown was assumed. The mass of Zirconia required for a crown is 3 g. Due to its larger vertical dimension, the 460 g Zirconia disc is useful when larger or more complex crowns are required, but in the case-study considered here, the 300 g and 460 g Zirconia discs yield the same number of standard crowns. It is assumed that 20 restorations can be milled from either disc. Consequently, the use of the 460 g disc leads to more waste per crown in the case considered here. Impact allocation was used to ensure that

only the relevant proportion of the total environmental impact of each disc was attributed to the crown in each case. The materials impact assessment for the CEREC one-time appointment workflow used single-restoration zirconia and LS2 blocks.

vii. Design and manufacture

In the conventional and digital workflows, a physical impression or a digital scan is the respective technical starting point for the manufacture of the definitive crown. The common workflow from this point is for the impression data to be sent to a dental technology laboratory for the design and manufacture. The alternative pathway of one-appointment clinical chair-side fabrication (CEREC, Dentsply Sirona) is modelled in the study, obviating the need for additional transport to the dental technology laboratory and a second patient journey for the fit of the restoration. The workflow that involves the dental technology laboratory considers transport to the laboratory according to three distances from the dental surgery: Local (10 km, via road with petrol van), national (200 km, via road with petrol van) and international (2000 km, air freight); all were based on the ecoinvent database (ecoinvent v3.10) and European Life Cycle Database. Allocation was applied as discussed in Section ix.

viii. End-of-life treatment

Two waste management scenarios, based on UK data from the ecoinvent database, were considered: Landfill and Mixed Treatment. The 'landfill scenario' assumed that all end-of-life treatment was handled by landfill, whereas the 'mixed treatment scenario' assumed the most likely waste stream for each material type. These were ascertained from product data, by considering the major parts in each piece of equipment, their materials, and thus the available waste streams. The landfill scenario assumed that all materials, including recyclable materials were disposed of in landfill; whereas the mixed scenario assumed separation of materials into non-recyclable materials, which would be disposed of in landfill or incineration, and recyclable products that would be subsequently recycled. For the one-appointment clinical chair-side fabrication (CEREC, Dentsply Sirona) end of life was modelled for the intraoral scanner, CAD/CAM milling machine and the furnace. Equipment lifetime and attribution

All the equipment used in the manufacture of dental crowns in this study has a useful lifetime. This is defined according to the following parameters: (i) technical reasons, such as how long the product lasts before it is no longer technically able to perform the required function; (ii) economic reasons, if for example, the owner wishes to sell the equipment, and ;(iii) obsolescence, if the practitioner wishes to replace the equipment with a newer/more efficient version. Product lifetimes of the Intra-oral scanner, milling unit and furnace are expected to be 7.5 years. These estimates are based on information from product manufacturers, which suggests product lifetimes should be between 5 and 10 years. Following discussion with experts, 7.5 years was selected as a mean lifetime.

To estimate the proportion of the total environmental impact for a piece of equipment attributable to each dental crown, it is first necessary to understand how many crowns each piece of equipment will contribute to over its lifetime. This is calculated based on the likely lifetime of the equipment, either in crowns per lifetime or calculated from a lifetime in years (as above) and a crowns per year estimate. The total impact of the product is then split across the number of crowns contributed to, giving a per crown value. The number of crowns contributed to each piece of equipment was estimated based on expert opinion and experience of the number of processes undertaken on an

average day. Assumptions made for product lifetimes and uses per year are shown in Table 2. Both product lifetime and number of processes per day are subject to variation, and can only ever be estimated. The impact of variation in these numbers was tested through Sensitivity Analysis using the tool described previously.

Energy associated with the digital units (e.g., intraoral scanner, milling machine, furnace) were accounted for and obtained from the manufacturer brochures and using UK National Grid electricity. In-use energy consumption in kWh per operation was used wherever available. In most cases, rated power was used to calculate energy consumption by multiplying the in-use time by the rated power (kW (rated power) x h (in-use time per use) = kWh) Standby energy use was calculated approximately and deemed negligible due to the use of modern efficient electronics, so was not considered. Consumption details are given in Appendix 1 (see Research Data).

Material attribution was based on the mass required per crown. 3 g is required for each Zirconia crown, and 2 g for each LS2 crown. Consequently, a crown requires 3 g of a 22.3 g Zirconia block, 3g of a 300 g Zirconia disc, and 3 g of a 460 g Zirconia disc. When LS2 is used, 2 g of a 12.3 g LS2 block is required per crown.

In recognition that one crown would not be an individual transport item but part of a larger payload, attribution was used. Transport attribution was based on the mass of the part being transported and the total expected payload of a vehicle. The total impact of the journey based on the appropriate method of transport and the mass transported by a normal full load was calculated, then a portion of this allocated to the dental crown.

ix. Patient travel

Patient travel is an important factor to consider in environmental and sustainability studies, specifically in dentistry, as it is required for patients to travel several times for different appointments. It is estimated that transport in dentistry contributes to 443 tonnes of nitrogen oxide a year [15]. Hence, it is important to consider patient travel for the different scenarios that this life cycle assessment includes for the fabrication of one ceramic dental crown. The considered distance that a patient travels from home to the dental practice was 7.57 miles per journey, the average distance travelled by dental patients in England by, calculated from NHS Business Authority data and reported by Public Health England [15,21].

x. Assumptions

Several parameters were defined as assumptions and listed below (Table 2). Assumptions are required to define the LCA, and are selected based on likely scenarios, experience and product knowledge. As highlighted above, knowledge of product lifetimes is required to understand the proportion of the impact of a product or process which should be attributed to one crown. In some cases, such as vehicle fuel, assumptions represent the statistically most likely scenario for the location in question at the present time (unleaded petrol). Laboratory transportation distance assumptions were based on three different scenarios (local, national and overseas) with distances of 10 km, 200 km and 2000 km, as in Table 2. It is assumed that all patient and staff travel (to dental clinic and return journey) is a fully dedicated trip (not shared with other tasks). For waste scenarios, according to the data collected from the manufacturer, most of the waste is disposed of by landfill, however recommendations are made to owners of the intraoral scanner, milling machines, 3D-printers and furnaces to dispose of these

devices according to the local regulations. Such regulations vary enormously across the world but predominantly involve landfill as the default scenario. To consider this variation, two waste treatment scenarios were considered for the main study: a) mixed treatment, where some of the parts are recycled; b) sanitary landfill. Major assumptions included in this study are given below (Table 2).

Table 2: Major assumptions product lifetimes and uses per year included in this study. Further details in Life Cycle Inventory table (Appendix 1, see Research Data)

Item	*Assumption value*
Clinic - Intraoral scans/year (multi-surgery practice performing 8 scans/day for assessments and treatment) x5 days/week x30weeks/year (assuming holidays and staff leave)	*1,200 scans per year*
Laboratory - CEREC Primemill millings of Lithium disilicate and zirconia blocks/discs (CEREC TESSERA, CEREC MTL, CERCON ht)	*8 millings per day*
Laboratory - Furnace (for lithium disilicate)	*6 cycles per day*
Laboratory - Furnace (for zirconia - not chairside)	*2 cycles per day*
Lifetime average of intraoral scanner, milling unit and furnace	*7.5 years*
Local transportation distance (Laboratory-Dental practice)	*10 km*
National transportation distance (Laboratory-Dental practice)	*200 km*
International transportation distance (Laboratory-Dental practice)	*2000 km*
Fuel for terrestrial transport of patients and laboratories	*Unleaded petrol*
Conventional workflow waste: Non-recycled scenario	*Municipal sanitary landfill*
Digital workflow waste: Non-recycled scenario	*Municipal sanitary landfill*
Digital workflow waste: Mixed treatment scenario	*Recycling and municipal sanitary landfill*

Results

Full comparative results

The results across all the eighteen impact categories were assessed, for seven scenarios. Results are presented as percentages. In each impact category, the scenario with the highest impact is shown at 100%, with others shown at their relative comparative impact (Figure 2). This figure illustrates the full life cycle assessment results for the three following cases: (i) The digital workflow with landfill end-of-life disposal, (ii) the digital workflow with mixed end-of-life treatment, and (iii) the conventional workflow with landfill end-of-life disposal.

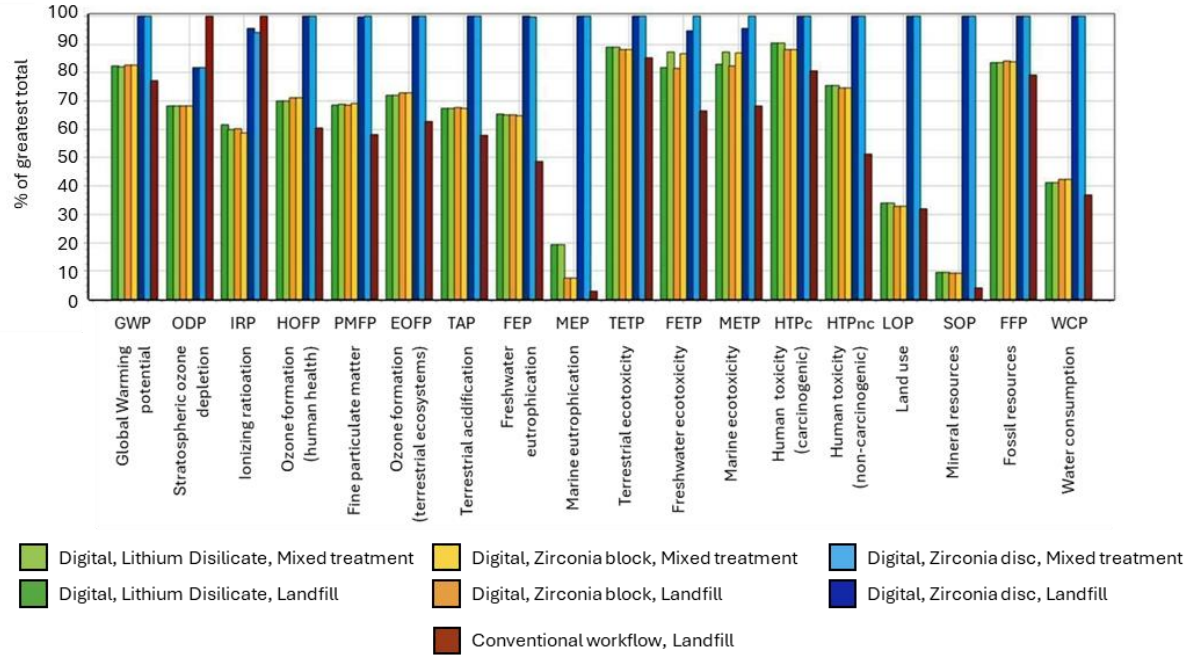


Figure 2: Percentage composition of LCIA indices for the digital workflow (DW) and the conventional workflow (CW) models, including type of ceramic material (Lithium Disilicate, Zirconia Block or Zirconia Disc) and waste management (mixed treatment or landfill). Passenger transport and local laboratory transport were considered in all scenarios.

Greenhouse gas impact results

For the digital workflow two scenarios were considered: Multiple patient appointments with remote dental technology laboratory (Figure 3 and 4) and a one single patient appointment with CEREC machinery (Figure 5).

The total Global Warming Potential (GWP) impacts in kg of carbon dioxide equivalent ($kgCO_2e$) are shown according to: (i) the crown fabrication ceramic (lithium disilicate block, zirconia disc or zirconia block) for each workflow; (ii) for the 'digital multiple appts' and 'conventional' workflows for both waste treatment scenarios with the inclusion of patient travel and laboratory transportation (Figure 3). This 'digital multiple appts' scenario creates 13.1 $kgCO_2e$ total impact (460 g zirconia disc) and 10.8 $kgCO_2e$ (LS2 block) (Table 3). The 'conventional' scenario creates 9.2 $kgCO_2e$ total impact. The highest impacts for both scenarios are directly attributed to patient transport accounting for 70% of the total 13.1 $kgCO_2e$ in the 'digital multiple appts' and 92% of the total 9.2 $kgCO_2e$ total impact in the 'conventional' scenario. Laboratory transportation had a negligible impact, regardless of the distance covered.

The total impacts in $kgCO_2e$ for the 'digital multiple appts' and 'conventional' workflows for both waste treatment scenarios with the exclusion of patient travel and laboratory transportation (Figure 4). This 'digital multiple appts' scenario creates 3.9 $kgCO_2e$ total GWP impact. The 'conventional' scenario creates 0.8 $kgCO_2e$ total impact. The highest impacts are directly attributed to the zirconia discs (460 g) accounting for 61% of the total 3.9 $kgCO_2e$ produced in this 'digital multiple appts' scenario. Printed resin models in the 'digital multiple appts' scenario were the next greatest impact and accounted for 20.5%. In the 'conventional' scenario the investment powder used in the manufacturing accounted for 75% of the total 0.8 $kgCO_2e$. Zirconia discs carry the highest impacts compared to other materials, irrespective of the waste management scenario.

The total impacts in $kgCO_2e$ for the 'digital one-time appt' workflow for the two CEREC ceramics in block form (lithium disilicate or zirconia), both waste treatment scenarios and with the exclusion of patient travel, laboratory transportation and printed resin models are shown in Figure 5. This 'digital one-time appt' scenario creates 0.6 $kgCO_2e$ total impact. The highest impacts are directly attributed to the CAD/CAM milling machine accounting for 50% of the total 0.6 $kgCO_2e$ produced in these scenarios. The actual fabrication materials (lithium disilicate or zirconia) and the intraoral scanner, each accounted for approximately 21% of the total 0.6 $kgCO_2e$ produced in these scenarios.

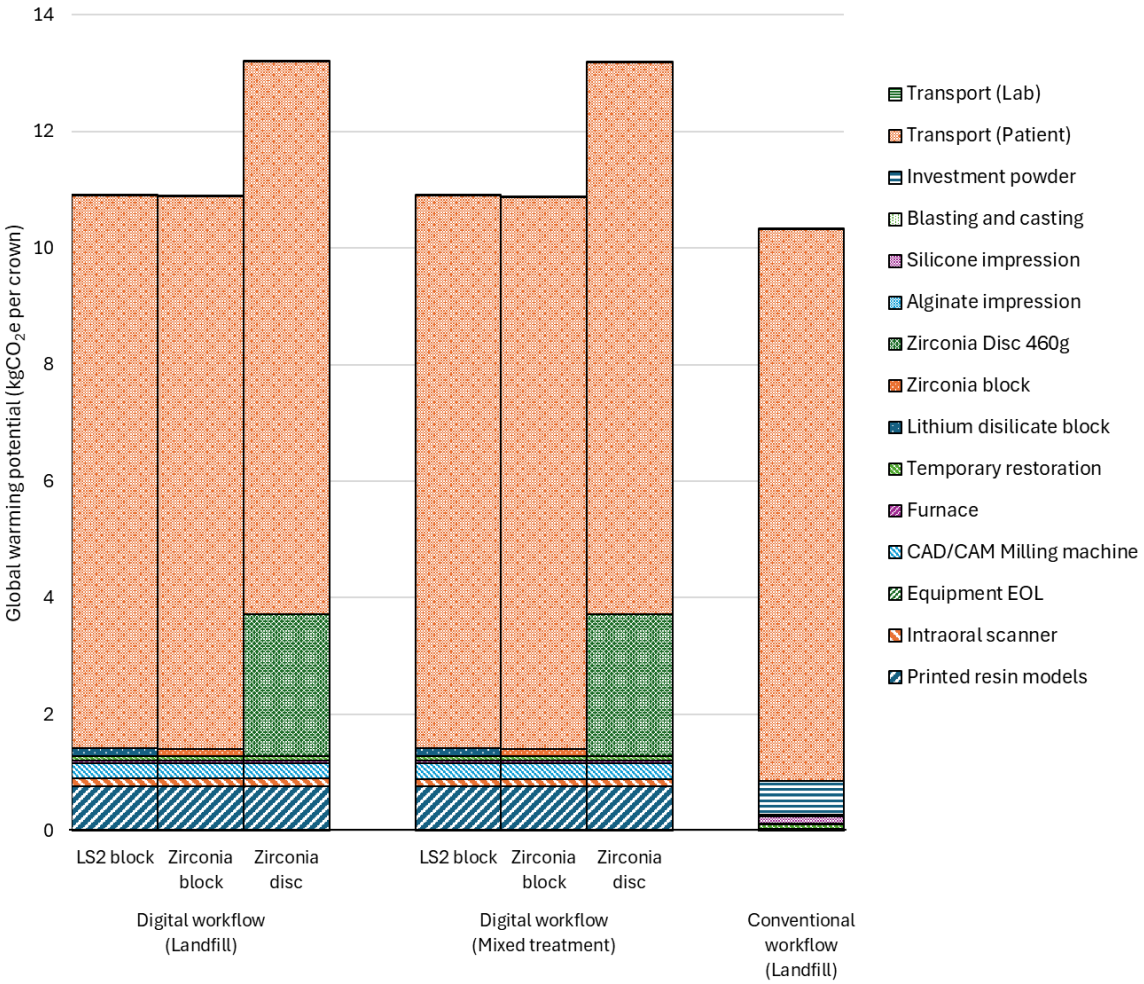


Figure 3: Total impact in $kgCO_2e$ per lithium disilicate and zirconia crown for digital and conventional workflow and two waste treatment scenarios (landfill and mixed treatment), including patient and laboratory transportation. NB: Laboratory transport [Transport (Lab)] contributes around 0.01% of total impact, and not visible on the graph.

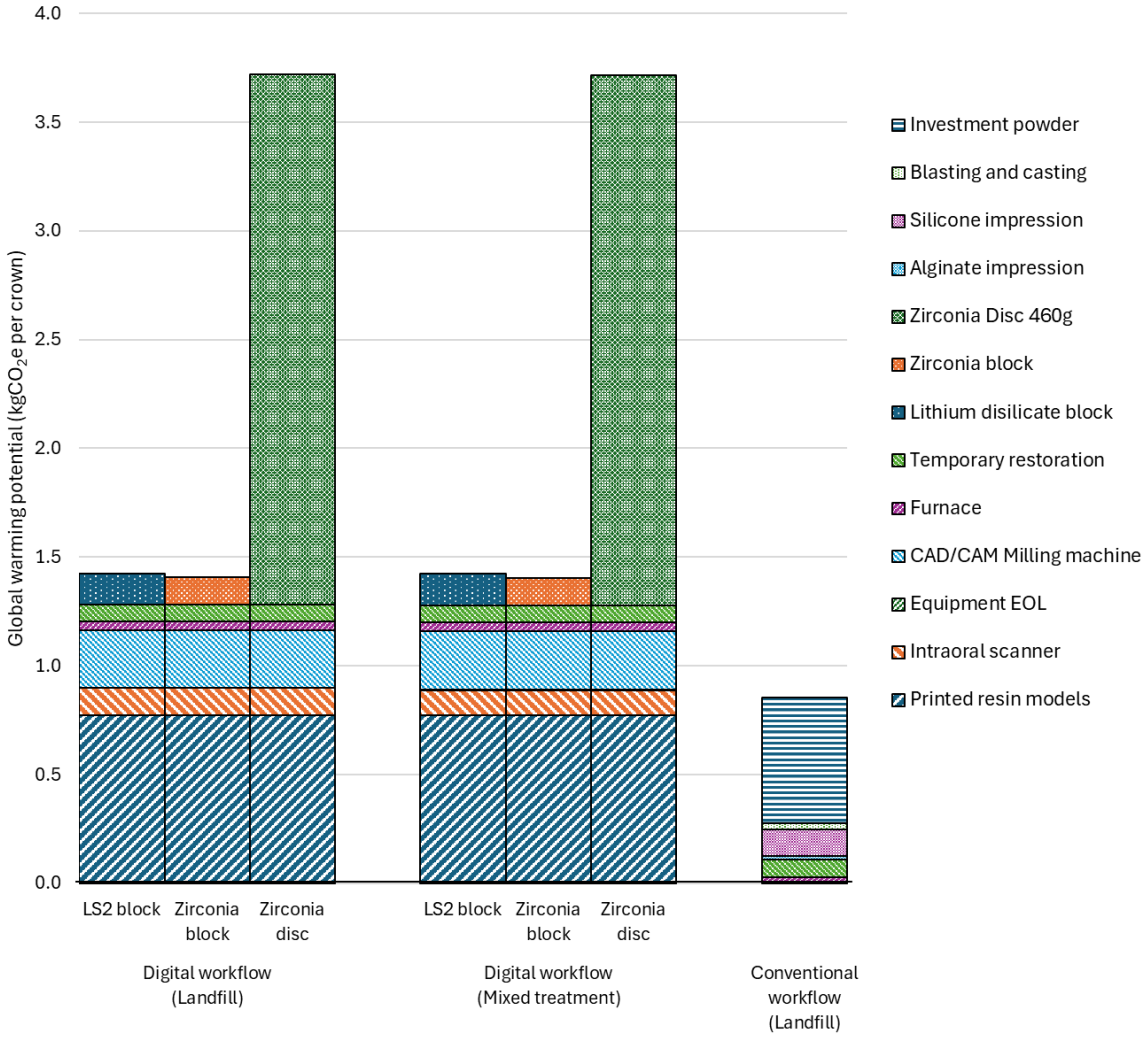


Figure 4: Total impact in kgCO_2e per lithium disilicate and monolithic zirconia crown for digital and conventional workflow and two waste treatment scenarios (landfill and mixed treatment), excluding patient and laboratory transportation.

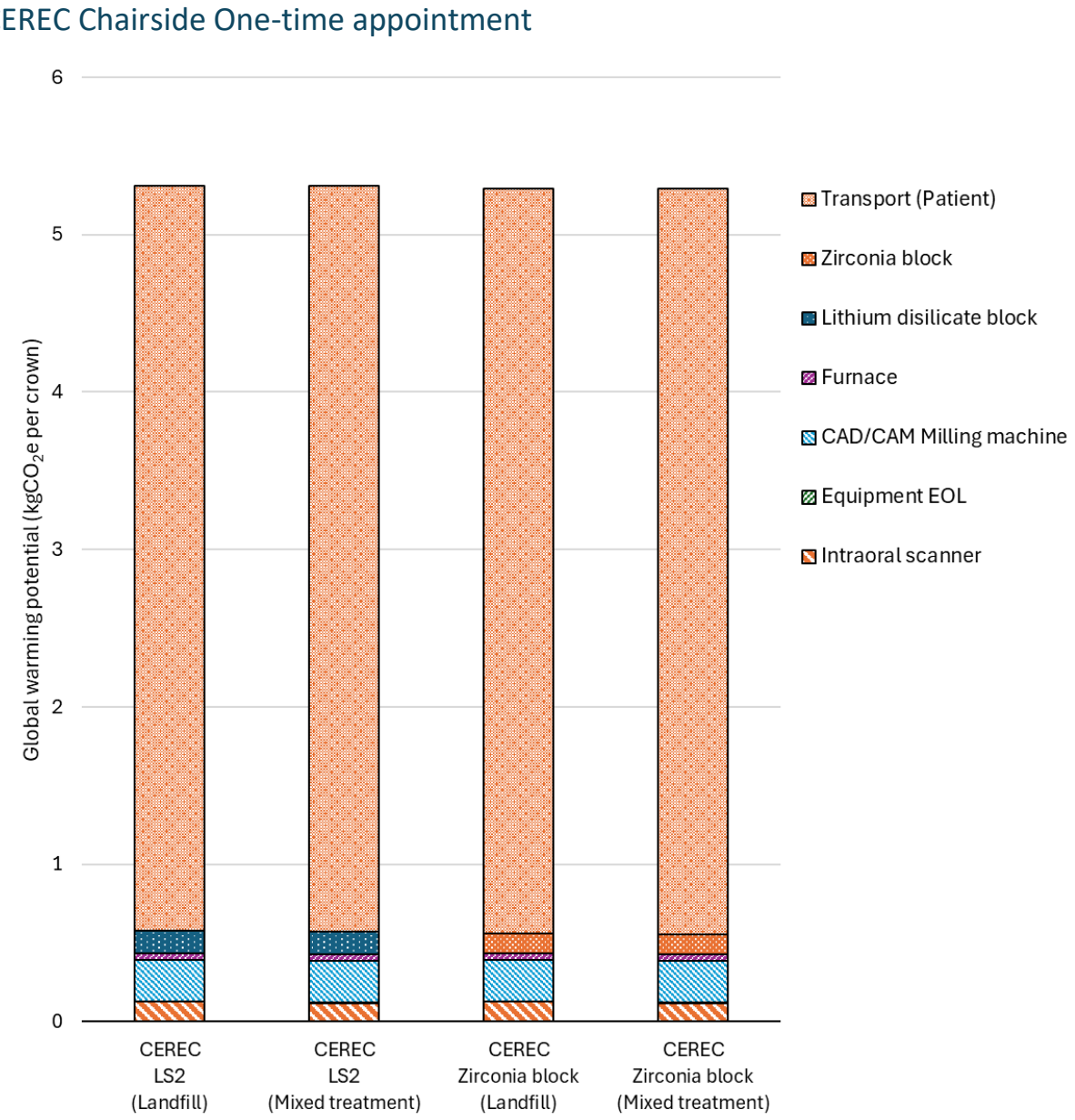


Figure 5: Total impact in $kgCO_2e$ per lithium disilicate and monolithic zirconia crown for full digital workflow in one appointment, and two waste treatment scenarios (landfill and mixed treatment), including patient transportation and excluding 3D-printed models.

Table 4 illustrates the contribution of main materials to the total impact in the conventional workflow and digital workflow cases.

Table 4: Global warming potential (GWP) values for the materials of conventional and digital workflow in $kgCO_2e$ per crown.

Conventional workflow materials		
Material	***Contribution value***	***Impact category (unit)***
Alginate	*0.0173*	*GWP ($kgCO_2e$)*

Silicone light	*0.0000971*	*GWP ($kgCO_2e$)*
Silicone putty	*0.00145*	*GWP ($kgCO_2e$)*
Aluminium oxide	*0.00274*	*GWP ($kgCO_2e$)*
Gypsum	*0.0141*	*GWP ($kgCO_2e$)*
Lithium disilicate	*0.0118*	*GWP ($kgCO_2e$)*
Digital workflow materials		
Material	***Contribution value***	***Impact category (unit)***
Printed resin models	*0.0156*	*GWP ($kgCO_2e$)*
Bis-Acryl composite (temporary crown)	*0.00000647*	*GWP ($kgCO_2e$)*
Lithium disilicate block	*0.142*	*GWP ($kgCO_2e$)*
Zirconia block	*0.124*	*GWP ($kgCO_2e$)*
Zirconia disc (460 g)	*2.43*	*GWP ($kgCO_2e$)*

Sensitivity Analysis

Table 3 shows the results for the digital (multiple appointments, excluding one-time appointment) and conventional workflows, showing overall total GHG (greenhouse gas) impact of a series of combined results for two workflows (digital and conventional), three materials (Lithium disilicate and Zirconia block, Zirconia disc 300 g and 460 g), three transport cases (local, national and international) and two end of life treatment cases (landfill and mixed). The highest impact per crown of all combined cases is the Zirconia disc case, with international transport and landfill treatment at end of life.

Table 3: Global Warming Potential (GWP) for Digital workflow with multiple appointments and Conventional workflow for three transport cases. Values in $kgCO_2e$ per lithium disilicate crown and zirconia crown, including 3D-printed models).

GWP ($kgCO_2e$) per crown	Fabrication workflow								
	Digital: Lithium Disilicate block		Digital: Zirconia block		Digital: Zirconia disc (460g)		Digital: Zirconia disc (300g)		Conventional
Waste treatment	Mixed (MT)	Landfill (LF)	MT	LF	MT	LF	MT	LF	LF
Local transport	10.89	10.90	10.87	10.79	13.18	13.19	12.39	12.41	9.27

National transport	10.89	10.90	10.87	10.88	13.18	13.19	12.49	12.41	9.31
International transport	10.89	10.90	10.88	10.88	13.19	13.20	12.40	12.41	9.36

Discussion

The development of rigorous methodologies to accurately quantify and compare environmental impacts is essential to support the adoption of more sustainable practices within dental and medical sectors. Although digital manufacturing approaches are frequently assumed to contribute reduced environmental impacts compared to conventional methods, there is a lack of evidence to support these claims. The aim of this study was to undertake an environmental comparative cradle to grave life-cycle assessment of conventional versus digital workflows for the fabrication of a dental ceramic crown. This study provides, for the first time, an assessment of the environmental impacts of each workflow and the key high impact 'hotspots', so that these can be addressed and mitigated effectively. Energy consumption, device transportation, patient travel, manufacturing and waste management were included in the model. The findings from this study and their associated interpretation are presented within the limitations of the established scope and premises.

As identified in previously published work [6,15,24], our study confirmed that the single greatest GWP impact arises from patient travel for dental appointments, regardless of the workflow chosen. Patient transportation was assumed by car with unleaded petrol, and although the number of appointments and the distances were the same for each workflow, this remains the greatest contribution overall, representing 88.2% of the total GWP (Figure 2). There is scope to mitigate the pollutant impact from patient travel with digital workflows that use chair-side one-time appointment scenarios. The use of transport (electric cars, public transport) based on renewable energies is a further mitigation strategy. Whilst patient transport involves a very significant impact. The transport distance of materials/prostheses between the dental practice and the technology laboratory has a small effect. Duane et al. reported on the environmental impact of patient and staff traveling to dental practices and laboratories and identified that dental technology laboratories that are 'local' to the dental practice will result in a smaller environmental pollution impact [15] reported on the environmental impact of patient and staff traveling to dental practices and laboratories and identified that dental technology laboratories that are 'local' to the dental practice will result in a smaller environmental pollution impact.

Although transport contributions were anticipated to be highly relevant, our key finding emerges from directly comparing the selected manufacturing workflows. Unexpectedly, conventional and digital practices are broadly similar for the overall environmental impacts, highlighting that careful analysis is essential for drawing conclusions and designing effective mitigation strategies.

When comparing the obtained data, the digital workflow shows an increased carbon footprint compared to the conventional route, with approximately 30% greater impact. However, it is important to note the assumptions that were made and the potential impact of these variables. For example, machinery lifetime is an important consideration - if the highlighted equipment were to last longer than the average calculated (7.5 years) or used more intensively (>8 intraoral scans and >11 millings per day), the use of the machinery will be increased within its lifetime, and this will result in an

improved environmental outcome. The energy consumption used for each type of equipment was obtained from the manufacturers' promotional and technical brochures and based on UK grid electricity, with electricity used in the UK and omitted energy used in standby mode or when used intermittently. In some cases, power use was calculated based on the voltage and maximum rated current for the equipment, meaning that this would only correspond to the maximum energy usage that is being consumed while the equipment is working at its higher efficiency, and does not consider when the equipment is turned on but on standby mode during the day. There is a further opportunity to mitigate the impacts from machinery, through effective recycling routes for component parts.

Another very important aspect to highlight is the inclusion of 3D-printed models as part of the digital workflow, which resulted in a higher impact compared to the conventional workflow. The ability to omit the 3D-printed model completely from the workflow would represent a further mitigation gain with a reduction of the GWP impact by approximately 0.8 $kgCO_2e$ per ceramic dental crown. This means that the total impact between digital and conventional workflows would be similar (9.891 and 9.301 $kgCO_2e$ respectively). For this LCA, the modelling of the 3D-printer and PMMA resin was based on a LCA study of desktop stereolithography reported by Mele et. al, [22]. The possibility of recycling these models is also a point for further investigation. In the 'one time appointment chair-side CEREC' digital workflow scenario, the 3D-printed models were omitted as their use is not necessary in these cases.

A hotspot mitigation opportunity focuses on a reduction of patient travel. A chair-side one-time appointment restoration provides a complete digital workflow with the intra-oral scan, restoration CAD/CAM process and crown cementation executed in one single clinical appointment.This scenario results in a reduction of the total impact of GHG emissions by approximately half, obtaining a result of 5.173 $kgCO_2e$ per dental crown.

When focusing on the material units that are used in the fabrication processes, it was observed that zirconia discs contribute the greatest impact, followed by 3D-printed models. This may be attributed to the ratio of the total disc weight and the amount of waste generated from millingan optimised quantity of dental crowns (20 zirconia dental crowns of 3 g each). The larger zirconia disc weighs 460 g and creates a total waste from milling twenty crowns of 400 g, that is disposed of in landfill. The ability to recycle the green state zirconia powder residue and reuse it for the fabrication of more zirconia dental crowns is the subject of current research [23]. A zirconia disc of 300 g was also modelled for this study, and the difference in GWP and waste can be seen in Table 3. The digital workflow with 460 g Zirconia disc has the highest impact across all transport and end of life cases, and the conventional workflow has the lowest.

Figure 2 shows the overall contribution of the digital workflow compared to the conventional workflow in the eighteen impact categories, where the digital pathway contribution is higher for both waste treatment scenarios (landfill and mixed treatment). This is associated with the extraction of raw materials and the manufacturing of the products (materials and equipment). Although the percentage differences observed in the GWP between the digital and conventional workflow are not substantial, this changes for the categories of marine eutrophication (MEP) and mineral resource scarcity (SOP). On the other hand, there is an important difference in the categories of stratospheric ozone depletion and ionizing radiation, where the conventional workflow surpasses the level % of all the digital workflow scenarios.

This study aimed to establish a baseline for understanding the environmental impacts of conventional and digital manufacturing pathways in dentistry, which will enable more accurate future comparisons. Although transport contributions were, as expected, very relevant, GWP results were found to be similar when directly comparing digital and conventional workflows. These findings challenge common assumptions and claims about the greater sustainability of digital approaches and provide useful insights for developing strategies to reduce environmental impacts in dentistry and related fields that use both traditional and emerging digital pathways.

Strengths and Limitations

For the first time, through a comprehensive comparative Life Cycle Assessment, we have a real appreciation of the environmental sustainability credentials of workflows (conventional vs digital) for the fabrication of a dental ceramic crown.

This study has established a knowledge baseline that identifies the true environmental impacts arising from these workflows and the hotspots points within the workflows that contribute most significantly.

This Life Cycle Assessment has followed ISO 14040:2006 and 14044:2006 standards, but is nonetheless subject to limitations. The eighteen environmental impact categories defined by the ReCiPe 2016 Midpoint Hierarchical impact assessment method v 1.09 method were calculated (Figure 2), but the detailed results presented subsequently consider Global warming potential (GWP) as the only impact category. GWP was selected as the key impact category since climate change impacts are of particular concern. However, though GWP is often treated as a proxy for environmental impact, there would be value in a future study considering a wider range of impact categories in more depth. The GWP results presented here highlight that Conventional and digital workflows have similar impact, but initial results suggest that this may not be the case in all impact categories.

The use of proxy data for three cases has the potential to reduce the accuracy of the results, however the selected proxies are very closely related to the original products, and none of these products contribute to the largest environmental impacts. Consequently, the impact of proxy use is likely to be small, though by definition, it is not possible to formally quantify the difference between proxy results and ideal case results. Sensitivity analysis was undertaken in areas of higher uncertainty (laboratory transport distance and end-of-life treatment).

The functional unit for this project of one dental ceramic crown (zirconia and lithium disilicate), manufactured and ready to cement provides clinically relevant data that enables appropriate analyses and the development of mitigation hotspots.

The UK context enabled the use of accurate region-specific data, improving the robustness of the results. The UK is considered representative of middle-high income countries enabling extrapolations to similar settings. The results from the LCA, identify that the actual workflow is not significantly influenced by neither the energy source nor waste management practices as these are applied equally to the different workflows. The number of patient journeys required to attend

clinical appointments stands out as the greatest factor, that is independent of national or regional settings.

The focus of this study does not include cost analysis and operative time assessments. Including these would expand the impact of the study beyond environmental impact, expanding our breadth and depth of knowledge in this field. These would require specific methodologies and extensive further modelling and have not been considered in this initial study.

Conclusions

Within the scope and premises of this study, this investigation provides for the first time a picture of the Global Warming Potential environmental impact of conventional and digital (multiple and single appointments) workflows and the key high-impact hotspots, so that these can be addressed and mitigated effectively. This provides the required knowledge base to inform more sustainable clinical practices and guide the dental community toward adopting more environmentally responsible approaches. Key conclusions are:

- Contrary to the prevailing assumption that digital workflows have a lower environmental impact, this study demonstrates that conventional and digital workflows are associated with similar overall environmental impacts. This study highlights that careful analysis is essential for drawing conclusions and designing effective mitigation strategies.
- The single greatest environmental impact (represented as GWP impact) arises from patient travel for dental appointments, regardless of the workflow chosen.
- A focus on the material units that are used in the fabrication processes, identified that zirconia discs contribute the greatest impact, followed by 3D-printed PMMA models.
- A series of practices are considered to mitigate the environmental impacts arising from the fabrication of a ceramic crown: Reduction in patient travel as much as practicable; avoid the use of printed 3D plastic physical models where feasible; maximise the workflow and productivity of all machinery and equipment; identify recycling and reuse of equipment and materials wherever possible.

Research data

The data used to calculate the Life Cycle Assessment 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.30247105, under the terms of the Creative Commons Attribution (CC BY-NC 4.0) licence.

Acknowledgments and Funding

The report published in this article is the outcome of the project ‘Comparative Life Cycle Assessment in clinical care: Conventional vs digital patient care pathways in dentistry’ conducted by the authorship between 2024-2025. The research team is grateful for the funding obtained from the following sources: The Engineering and Physical Sciences Research Council, UK - Impact Acceleration Account (EPSRC IAA), grant number R/183714-11-1 (£55,656) and DENTSPLY SIRONA Inc., grant number R/183714-12-1 (£75,000). Moreover, the research team wishes to acknowledge that this project was

made possible thanks to the further contributions (leadership and product data) from scientists in the various Departments of DENTSPLY SIRONA Inc. We would like to identify: Mihaela Chidean (Sr. Corporate Communications Manager); Tobias Rösch (Product Development Engineer); Lothar Völkl (Senior Manager Development & Application Technology). The research team is very grateful for their invaluable contributions.

References

1. Demirel M, Diken Türksayar AA, Petersmann S, Spintzyk S, Donmez MB. Dimensional Stability of Additively Manufactured Dentate Maxillary Diagnostic Casts in Biobased Model Resin. Materials (Basel). 2024 May 1;17(9):2128. doi: 10.3390/ma17092128. PMID: 38730934; PMCID: PMC11084617(9).6.

2. Suese K. Progress in digital dentistry: The practical use of intraoral scanners. Dent Mater J. 2020 Jan 31;39(1):52-56. doi: 10.4012/dmj.2019-224. Epub 2019 Nov 14. PMID: 31723066.

3. Galante R, Figueiredo-Pina CG, Serro AP. Additive manufacturing of ceramics for dental applications: A review. Dent Mater. 2019 Jun;35(6):825-846. doi: 10.1016/j.dental.2019.02.026. Epub 2019 Apr 2. Erratum in: Dent Mater. 2023 Sep;39(9):860. doi: 10.1016/j.dental.2023.08.001. PMID: 30948230.

4. Turkyilmaz I, Lakhia S. Challenges to Digital Dentistry in Dental Schools. J Contemp Dent Pract. 2019 Dec 1;20(12):1361. PMID: 32381832.

5. Martin N, Mulligan S, Shellard IJ, Hatton PV, editors. Consensus on Environmentally Sustainable Oral Healthcare: A Joint Stakeholder Statement. York (UK): White Rose University Press; 2022 Dec. PMID: 38687834.

6. Suresh P, Crotty J, Tesanovic S, Alaweed O, Doyle S, Kiandee M, Hayes E, Umeh V, Khalilinejad B, Duane B. A life cycle analysis of the environmental impact of procurement, waste and water in the dental practice. Br Dent J. 2024 Apr;236(7):545-551. doi: 10.1038/s41415-024-7239-5. Epub 2024 Apr 12. PMID: 38609622; PMCID: PMC11014795.

7. International Organization for Standardization. (2019). *Dentistry - Polymer-based restorative materials (ISO standard No. 4049:2019).* https://www.iso.org/standard/67596.html (Accessed December 2025)

8. International Organization for Standardization*. (2024). Dentistry - Ceramic materials (ISO standard No. 6872:2024).* https://www.iso.org/standard/81718.html (Accessed December 2025)

9. Sulaiman TA. Materials in digital dentistry-A review. J Esthet Restor Dent. 2020 Mar;32(2):171-181. doi: 10.1111/jerd.12566. Epub 2020 Jan 13. PMID: 31943720.

10. Cervino G, Fiorillo L, Herford AS, Laino L, Troiano G, Amoroso G, Crimi S, Matarese M, D'Amico C, Nastro Siniscalchi E, Cicciù M. Alginate Materials and Dental Impression Technique: A Current State of the Art and Application to Dental Practice. Mar Drugs. 2018 Dec 29;17(1):18. doi: 10.3390/md17010018. PMID: 30597945; PMCID: PMC6356954.

11. Ma L, Xie Q, Evelina A, Long W, Ma C, Zhou F, Cha R. The Effect of Different Additives on the Hydration and Gelation Properties of Composite Dental Gypsum. Gels. 2021 Aug 11;7(3):117. doi: 10.3390/gels7030117. PMID: 34449595; PMCID: PMC8395839.

12. Oyar P, Can G, Atakol O. Effects of environment on the release of Ni, Cr, Fe, and Co from new and recast Ni-Cr alloy. J Prosthet Dent. 2014 Jul;112(1):64-9. doi: 10.1016/j.prosdent.2013.09.022. Epub 2013 Dec 25. PMID: 24370387.

13. Batra S, Detroja X, Biradar A, Jayaprakash K, Mohammed NZ, Rijesh M. Bulk Recycling of Ni-Cr-Mo Dental Alloy - A Sustainable Approach. ASM Science Journal. 18. 1-10. 10.32802/asmscj.2023.1318.

14. Jeong M, Radomski K, Lopez D, Liu JT, Lee JD, Lee SJ. Materials and Applications of 3D Printing Technology in Dentistry: An Overview. Dent J (Basel). 2023 Dec 19;12(1):1. doi: 10.3390/dj12010001. PMID: 38275676; PMCID: PMC10814684.

15. Duane B, Steinbach I, Ramasubbu D, Stancliffe R, Croasdale K, Harford S, Lomax R. Environmental sustainability and travel within the dental practice. Br Dent J. 2019 Apr;226(7):525-530. doi: 10.1038/s41415-019-0115-z. PMID: 30980009.

16. Sailer I, Makarov NA, Thoma DS, Zwahlen M, Pjetursson BE. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: Single crowns (SCs). Dent Mater. 2015 Jun;31(6):603-23. doi: 10.1016/j.dental.2015.02.011. Epub 2015 Apr 2. Erratum in: Dent Mater. 2016 Dec;32(12):e389-e390. doi: 10.1016/j.dental.2016.09.032. PMID: 25842099.

17. Pjetursson BE, Sailer I, Merino-Higuera E, Spies BC, Burkhardt F, Karasan D. Systematic review evaluating the influence of the prosthetic material and prosthetic design on the clinical outcomes of implant-supported multi-unit fixed dental prosthesis in the posterior area. Clin Oral Implants Res. 2023 Sep;34 Suppl 26:86-103. doi: 10.1111/clr.14103. PMID: 37750526.

18. Pjetursson BE, Valente NA, Strasding M, Zwahlen M, Liu S, Sailer I. A systematic review of the survival and complication rates of zirconia-ceramic and metal-ceramic single crowns. Clin Oral Implants Res. 2018 Oct;29 Suppl 16:199-214. doi: 10.1111/clr.13306. PMID: 30328190.

19. Pjetursson BE, Sailer I, Makarov NA, Zwahlen M, Thoma DS. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part II: Multiple-unit FDPs. Dent Mater. 2015 Jun;31(6):624-39. doi: 10.1016/j.dental.2015.02.013. Epub 2015 Apr 30. Erratum in: Dent Mater. 2017 Jan;33(1):e48-e51. doi: 10.1016/j.dental.2016.09.033. PMID: 25935732.

20. Hallmann L, Ulmer P, Kern M. Effect of microstructure on the mechanical properties of lithium disilicate glass-ceramics. J Mech Behav Biomed Mater. 2018 Jun;82:355-370. doi: 10.1016/j.jmbbm.2018.02.032. Epub 2018 Mar 3. PMID: 29655121.

21.Carbon modelling within dentistry Towards a sustainable future [Internet]. 2018. Available from: https://www.gov.uk/government/publications/carbon-modelling-within-dentistry-towards-a-sustainable-future

22. Mele, Mattia & Campana, Giampaolo & D'Avino, Giulia. (2019). Life cycle impact assessment of desktop stereolithography. Journal of Cleaner Production. 244. 118743. 10.1016/j.jclepro.2019.118743.

23. Yang H, Sun L, Yu H, Nugraha AP, Vanegas Sáenz JR, Hong G. Current prospect of dental zirconia recycling: A scoping review. J Prosthodont Res. 2024 Oct 16;68(4):522-531. doi: 10.2186/jpr.JPR_D_23_00186. Epub 2024 Mar 23. PMID: 38522896.

24. Künzle P, Frank AC, Paris S. Environmental Impact of a Tooth Extraction: Life Cycle Analysis in a University Hospital Setting. Community Dent Oral Epidemiol. 2026 Feb;54(1):30-39. doi: 10.1111/cdoe.70003. Epub 2025 Jun 27. PMID: 40579390; PMCID: PMC12808852.

25.Nilsson AE, Bergman K, Gomez Barrio LP, Cabral EM, Tiwari BK. Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy. Algal Research. 65. 102725. 10.1016/j.algal.2022.102725.