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Evaluating The Sustainability Of Stainless Steel Crowns And Zirconia Crowns In Pediatric Patients

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Abstract:
Background: *Stainless steel crowns (SSCs) and zirconia crowns are the primary choices for full-coverage restorations of severely decayed primary molars. While clinical efficacy is well-documented, a comprehensive sustainability assessment, encompassing environmental, economic, and social factors, is lacking.*
Methods: *This prospective, comparative clinical study involved 120 children (aged 4-7 years) requiring a full-coverage restoration on a primary molar. Patients were randomly allocated to receive either an SSC (n=60) or a zirconia crown (n=60). Clinical performance (Gingival Index, Plaque Index, survival rate) was evaluated at 6, 12, and 24 months. A cradle-to-grave LCA was performed to quantify environmental impact, focusing on Global Warming Potential (GWP). Economic analysis included material costs, chair-side time, and re-treatment needs. Parental satisfaction with aesthetics and overall experience was measured using a 10-point Visual Analog Scale (VAS) at 12 months. Data were analyzed using independent t-tests and Chi-square tests (α = 0.05).*
Results: *At 24 months, both crown types demonstrated high survival rates (SSC: 96.7%, Zirconia: 95.0%; p=0.654). Zirconia crowns showed significantly better gingival health (Gingival Index: 0.45 ± 0.18 vs. SSC: 0.88 ± 0.24; p<0.001). The LCA revealed a significantly higher environmental impact for zirconia crowns (GWP: 1.32 ± 0.11 kg CO_2-eq vs. SSC: 0.79 ± 0.09 kg CO_2-eq; p<0.001). The total cost per restoration was substantially lower for SSCs ($142.50 ± $15.80 vs. Zirconia: $295.70 ± $28.40; p<0.001). Parental satisfaction with aesthetics was overwhelmingly higher for zirconia crowns (VAS score: 9.3 ± 0.6 vs. SSC: 3.8 ± 1.2; p<0.001).*
Conclusion: *A significant trade-off exists in the sustainability of pediatric crowns. SSCs exhibit superior environmental and economic sustainability, making them a pragmatic choice for public health applications. In contrast, zirconia crowns offer distinct advantages in biocompatibility and aesthetics, aligning with patient-centered social sustainability goals. The selection of crown material requires a balanced consideration of these competing factors to achieve truly sustainable pediatric dental care.*
Keywords: *Pediatric Dentistry, Stainless Steel Crown, Zirconia Crown, Sustainability, Life Cycle Assessment, Cost-Effectiveness, Patient-Reported Outcomes.*

INTRODUCTION

Early Childhood Caries (ECC) remains a significant global health issue, affecting a large proportion of preschool-aged children and leading to pain, infection, and impaired quality of life **[1]**. When primary molars suffer extensive carious lesions, full-coronal restorations are indicated to restore function, maintain arch space, and prevent premature tooth loss. For decades, the pre-formed stainless steel crown (SSC) has been considered the "gold standard" for this purpose. SSCs are renowned for their durability, cost-effectiveness, and ease of placement, demonstrating excellent long-term clinical success rates **[2]**. However, they possess notable disadvantages, including poor aesthetics and the presence of nickel, which can elicit hypersensitivity reactions in a small subset of patients.

In response to growing parental demand for more aesthetic and biocompatible alternatives, monolithic zirconia crowns have emerged as a popular option in pediatric dentistry **[3]**. Zirconia offers superior aesthetics, high flexural strength, and excellent tissue response, with studies reporting favorable clinical outcomes comparable to SSCs in terms of longevity and gingival health **[4]**. Despite their clinical and aesthetic benefits, zirconia crowns are associated with higher material costs, greater technique sensitivity during placement, and concerns regarding potential wear of the opposing dentition.
The discourse comparing SSCs and zirconia crowns has traditionally been confined to clinical parameters such as longevity, marginal integrity, and gingival response. However, the modern concept of sustainability in healthcare mandates a more holistic evaluation, extending beyond mere clinical performance **[5]**. True sustainability is a multi-dimensional construct resting on three pillars: environmental stewardship, economic viability, and social equity/acceptability. In dentistry, this translates to evaluating the entire life cycle of materials—from raw material extraction and manufacturing to clinical use and final disposal—alongside their economic implications and impact on patient well-being **[6]**.
Recent studies in restorative dentistry have begun to apply Life Cycle Assessment (LCA) to quantify the environmental footprint of various materials and procedures, revealing significant hidden environmental costs associated with material processing and energy consumption **[7]**. However, such comprehensive analyses are notably absent in the field of pediatric dentistry, particularly concerning full-coronal restorations. The choice between an SSC and a zirconia crown currently relies on a narrow set of clinical and aesthetic considerations, overlooking the broader environmental and economic consequences. This represents a significant research gap. Understanding the full sustainability profile of these commonly used restorations is critical for informing evidence-based clinical guidelines, guiding healthcare policy, and empowering clinicians and parents to make more responsible and informed decisions.
Therefore, the aim of this study was to conduct a multi-faceted comparative evaluation of the sustainability of stainless steel crowns and zirconia crowns in pediatric patients. This assessment integrated four key domains: (1) clinical performance over 24 months, (2) environmental impact through a cradle-to-grave Life Cycle Assessment, (3) economic analysis of total restoration cost, and (4) social acceptability based on parent-reported outcomes.

MATERIALS AND METHODS

Study Design and Setting

This study was a prospective, single-center, randomized controlled clinical trial with an integrated life cycle and cost analysis.

Sample Size and Selection

A sample size of 120 participants was calculated using a power analysis (G*Power 3.1) to detect a clinically significant difference of 0.5 in the mean Gingival Index score between groups with 90% power and an alpha of 0.05, assuming a standard deviation of 0.7.
A total of 120 healthy children were recruited. Inclusion criteria were: (1) age between 4 and 7 years; (2) presence of at least one primary molar requiring a full-coverage restoration due to extensive caries or following pulpotomy; (3) cooperative behavior (Frankl behavior rating of 3 or 4); and (4) parental consent. Exclusion criteria included: (1) known allergy to nickel or other metal alloys; (2) severe bruxism; (3) compromising medical conditions; and (4) inability to return for follow-up appointments.
Participants were randomly allocated into two equal groups (n=60 per group) using a computer-generated randomization sequence:

- **Group 1 (SSC):** Received a pre-formed stainless steel crown (3M™ ESPE™).
- **Group 2 (Zirconia):** Received a pre-formed monolithic zirconia crown (Nusmile® ZR).

Clinical Procedure

All procedures were performed by two calibrated pediatric dental specialists. Following local anesthesia and rubber dam isolation, carious tissue was removed, and pulpotomy was performed if indicated. Tooth preparation was conducted according to the manufacturer's guidelines for each crown type. For the SSC group, minimal tooth reduction was performed. For the zirconia group, a more defined circumferential and occlusal reduction was required. Crowns were luted with a glass ionomer cement (Ketac™ Cem). Post-operative radiographs were taken to confirm marginal fit.

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Outcome Measures

Clinical Performance: Evaluations were conducted at 6, 12, and 24 months by a blinded examiner.
Gingival Index (GI): Measured according to Löe and Silness on four surfaces of the crowned tooth.
Plaque Index (PI): Measured according to Silness and Löe on four surfaces of the crowned tooth.
Crown Survival: Assessed using modified United States Public Health Service (USPHS) criteria. Failure was defined as crown loss, perforation, fracture, or secondary caries requiring replacement.

1. **Environmental Impact (LCA):** A cradle-to-grave LCA was conducted using SimaPro 9.2 software and the Ecoinvent 3.6 database. The functional unit was defined as "one full-coronal restoration providing clinical service for a 24-month period." The assessment included raw material extraction (chromium, iron, nickel for SSCs; zirconium sand for zirconia), manufacturing (smelting, machining, sintering), transportation, clinical placement (energy for equipment, consumables), and end-of-life (landfill). The primary impact category analyzed was Global Warming Potential (GWP), expressed in kg of carbon dioxide equivalents (CO_2-eq).
2. **Economic Analysis:** A micro-costing approach was used. Costs recorded included: (1) crown material cost; (2) cost of all consumables (cement, burs, etc.); and (3) chair-side time, converted to a monetary value based on clinic overheads. The total cost per restoration was calculated.
3. **Social Acceptability (Parent-Reported Outcome):** At the 12-month follow-up, parents/guardians were asked to rate their satisfaction with the crown's aesthetics and their overall satisfaction on a 10-point Visual Analog Scale (VAS), where 0 represented "extremely dissatisfied" and 10 represented "extremely satisfied."

Statistical Analysis

All data were analyzed using SPSS software, version 27.0 (IBM Corp.). Descriptive statistics (mean, standard deviation, percentages) were calculated. Independent t-tests were used to compare continuous data (GI, PI, cost, LCA impact, VAS scores) between the two groups after confirming normality with the Shapiro-Wilk test. The Chi-square test was used to compare categorical data (gender, tooth type, survival rates). The level of statistical significance was set at $p < 0.05$.

RESULTS

A total of 120 crowns were placed (60 SSC, 60 Zirconia). All 120 patients completed the 24-month follow-up. The demographic and clinical characteristics of the participants were well-matched between the two groups at baseline, with no statistically significant differences observed (Table 1).

Table 1. Baseline Demographic and Clinical Characteristics of Study Participants

Characteristic	SSC Group (n=60)	Zirconia Group (n=60)	p-value
Mean Age (years ± SD)	5.4 ± 1.1	5.6 ± 0.9	0.381
Gender (Male/Female)	32 / 28	29 / 31	0.592
Tooth Type			0.815
First Primary Molar	25 (41.7%)	27 (45.0%)	
Second Primary Molar	35 (58.3%)	33 (55.0%)	
Jaw			0.744
Maxillary	28 (46.7%)	31 (51.7%)	
Mandibular	32 (53.3%)	29 (48.3%)	

SD: Standard Deviation. p-values calculated using independent t-test for age and Chi-square test for categorical variables.

Clinical Outcomes

At the 24-month follow-up, both crown types demonstrated high overall survival rates with no statistically significant difference (p=0.654). Two SSCs failed (one due to perforation, one due to loss of retention) and three zirconia crowns failed (two due to fracture, one due to loss of retention). Zirconia crowns were associated with significantly lower mean Gingival Index and Plaque Index scores compared to SSCs ($p<0.001$ for both). These results are summarized in Table 2.

Table 2. Clinical Outcomes at 24-Month Follow-up

Outcome Measure	SSC Group (n=60)	Zirconia Group (n=60)	p-value
Survival Rate (%)	96.7% (58/60)	95.0% (57/60)	0.654
Mean Gingival Index (± SD)	0.88 ± 0.24	0.45 ± 0.18	<0.001
Mean Plaque Index (± SD)	1.15 ± 0.31	0.62 ± 0.25	<0.001

p-values calculated using Chi-square test for survival rate and independent t-test for index scores.

Sustainability Metrics

The integrated sustainability analysis revealed stark differences between the two crown types. The LCA showed that the production and placement of a zirconia crown resulted in a significantly higher Global Warming Potential than an SSC. Similarly, the total cost of a zirconia crown restoration was more than double that of an SSC. Conversely, parental satisfaction with aesthetics was profoundly higher for the zirconia group. These findings are detailed in Table 3.

Table 3. Comparative Sustainability Metrics per Restoration

Sustainability Pillar & Metric	SSC Group (n=60)	Zirconia Group (n=60)	p-value
Environmental			
Global Warming Potential (kg CO_2-eq ± SD)	0.79 ± 0.09	1.32 ± 0.11	<0.001
Economic			
Total Cost (USD ± SD)	$142.50 ± $15.80	$295.70 ± $28.40	<0.001
Social			
Parental VAS - Aesthetics (± SD)	3.8 ± 1.2	9.3 ± 0.6	<0.001
Parental VAS - Overall (± SD)	8.1 ± 1.0	9.1 ± 0.8	<0.001

VAS: Visual Analog Scale (0-10 scale). p-values calculated using independent t-test.

DISCUSSION

This study provides a novel, multi-faceted sustainability assessment of stainless steel and zirconia crowns in pediatric dentistry, moving beyond traditional clinical comparisons. Our findings reveal a complex trade-off between the environmental, economic, and social dimensions of sustainability, indicating that neither material is unequivocally superior across all domains.

In terms of clinical performance, our results align with the existing literature. Both crown types exhibited excellent survival rates over 24 months, confirming their reliability for restoring primary molars **[8]**. The significantly better gingival health and lower plaque accumulation observed with zirconia crowns are also consistent with previous studies **[4, 9]**. This is likely attributable to zirconia's high biocompatibility, smooth polished surface that resists plaque adhesion, and potential for more precise marginal adaptation compared to the crimped margins of SSCs. The slightly higher plaque retention on SSCs may contribute to the increased gingival inflammation noted in that group.

The most striking findings of this study emerge from the environmental and economic analyses. The Life Cycle Assessment demonstrated that zirconia crowns have a substantially higher carbon footprint. This is primarily due to the energy-intensive manufacturing process, which involves mining zirconium sand, complex chemical purification to produce zirconia powder, and high-temperature sintering (often above 1500°C) to achieve its final dense, strong form **[10-15]**. In contrast, while the production of stainless steel from iron ore and other alloys is also energy-intensive, the overall process is more established and less complex per unit. Furthermore, SSCs have a higher potential for recycling at end-of-life, although this is rarely realized in a clinical waste context. This finding underscores the hidden environmental cost of advanced ceramic materials and challenges the notion that "metal-free" is inherently "greener" **[7]**.

From an economic perspective, SSCs were unequivocally more sustainable. The cost of a zirconia crown restoration was over twice that of an SSC, a difference driven by higher material costs and slightly longer chair-side time required for the more precise tooth preparation. This significant cost disparity has profound implications for public health dentistry and accessibility of care, particularly in publicly funded healthcare systems or for families with limited financial resources. The cost-effectiveness of SSCs solidifies

their role as a pragmatic and equitable solution for managing ECC on a population level.
The social pillar of sustainability, represented here by parental satisfaction, presented a contrasting picture. Parents overwhelmingly preferred the tooth-colored appearance of zirconia crowns, as reflected in the near-perfect VAS scores for aesthetics. This is unsurprising and aligns with a broader societal trend favouring aesthetic dental solutions **[11,16]**. The improved aesthetics can positively impact a child's self-esteem and reduce potential psychosocial stigma associated with metallic restorations. This strong parental preference is a powerful driver for the adoption of zirconia crowns in clinical practice and represents a critical component of patient-centered care.
This study is not without limitations. It was a single-center trial, which may limit the generalizability of the findings. The 24-month follow-up period is adequate for primary molars but does not capture the full service life of the restoration. The LCA was based on modeling using established databases and contains inherent assumptions; specific manufacturing data from each company could refine the results. Finally, our assessment of social sustainability was limited to parental satisfaction and did not include a formal pediatric quality of life instrument.

CONCLUSION

Within the limitations of this study, it is concluded that a clear sustainability trade-off exists between stainless steel and zirconia crowns for pediatric patients.

- **Stainless steel crowns (SSCs)** demonstrate superior environmental and economic sustainability, with a lower carbon footprint and significantly lower cost, making them a highly effective and accessible public health tool.
- **Zirconia crowns** excel in the social and clinical biocompatibility domains, offering superior aesthetics that lead to higher parental satisfaction and promoting better gingival health.

The choice between these two restorative materials is therefore not a simple one. It requires a shared decision-making process involving the clinician and the parent, where the clinical needs of the child are balanced against parental values, financial considerations, and a broader awareness of the environmental impact of healthcare choices. Future research should focus on developing more sustainable dental materials that do not force a compromise between ecological responsibility, affordability, and patient-centered outcomes.

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