RESEARCH PAPER

Advances in Drug Delivery Systems in Operative Dentistry for Caries Management and Pulp Protection

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Abstract

Drug delivery systems (DDS) are becoming more and more a part of operative dentistry to enhance caries control and pulp protection, as localized, sustained or stimuli-responsive therapeutic action at the tooth restoration interface and in pulp-facing tissues. The objective of this systematic literature review was to summarize the progress in the field of DDS that is used in the caries control (including secondary caries prevention and remineralization) and pulp protection/vital pulp therapy. Scopus, PubMed, Web of Science, ScienceDirect, and Google Scholar were searched under the guidance of PRISMA with the assistance of manual reference checking. Following the elimination of duplicates and two-step screening, full texts were evaluated on the basis of preset eligibility criteria. A structured template of the data was analyzed to extract data of type platform, payload/function, outcome and setting of the study and risk of bias was assessed through design-appropriate tools and the synthesis of findings was made narratively as the data were heterogeneous. Out of 163 records found, 25 studies were obtained. The most common clusters of evidence in support of caries management (DDs: antimicrobial delivery, nano-enabled remineralization, and ion-releasing restorative systems) and pulp protection (DDs: injectable/functional hydrogel matrices, drug-releasing pulp-capping cements, and sustained-release regenerative designs) were presented; but the similarity of outcomes measures and the insufficient clinical validation limited the comparability. Altogether, multifunctional, locally active materials are on the way to become a reality of DDS-enabled operative dentistry, however, additional standardized testing and more robust clinical evidence are required to establish long-term efficiency.

Keywords: Operative dentistry; Drug delivery systems; Dental caries; Secondary caries; Remineralization; Pulp protection; Vital pulp therapy; Controlled release; Nanoparticles; Hydrogels

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1. Introduction

Operative dentistry is becoming less surgical and more of a drill-and-fill mode with more emphasis directed toward biologically based caries management that attempts to control biofilms, promote remineralization and maintain pulp vitality. Here, drug delivery systems (DDS) have received interest since they can be used as a localized, sustained, and condition-responsive delivery of therapeutic agent at the tooth surface, in carious lesions, and at the tooth-restoration interface. This tendency is reflected in nanotechnology-mediated remineralization schemes whereby self-assembled nanostructures and nanocomplexes can be used to facilitate mineral deposition and surface repair to aid caries control using targeted delivery of remineralizing components[1]. Equally, antibacterial restorative strategies are shifting to the materials that release antimicrobials over time, including resin composites that emit chlorhexidine, which targets the decreased recolonization of bacteria and lowered chances of secondary caries around the restorations[2].

In addition to these material-based strategies, a few general trends in dental DDS focus on nanoscale carriers and designed platforms of infection control and

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therapeutic targeting in dentistry. Nano drug delivery systems have been noted as an emerging field with a high growth rate that can enhance localization, bioavailability, and persistence of therapeutic agents in the mouth cavity[3]. Specifically, recent evidence synthesis on nanosystems in caries prevention and treatment highlights the potential of carriers that remain therapeutically active despite salivary clearance and changing pH in favor of the clinical requirement of controlled-release and stimuli-responsive approaches[4]. In addition to caries control, the DDS concepts are also being used to protect pulp, with new pulp-capping materials being developed to behave as bioactive barriers and delivery vectors; hydrogel composites with bioactive elements have been described as possible pulp-capping systems to promote healing and regenerative effects[5].

The emergence of the next generation restorative materials further illustrates how operative dentistry is shifting to multifunctional systems to combine antibacterial activity with remineralizing potential and enhanced longevity including restorative resin composites with integrated therapeutic functions[6]. Under pulp-preservation approaches, injectable biomaterials have been considered due to their capability to deliver localized therapeutic conditions and to promote dentin regeneration demonstrated by studies into treated dentin matrix hydrogels to be used in pulp-capping[7]. One of the major causes of restoration failure is the incorporation of DDS as a component of adhesive interfaces, with pH responsive dentin adhesives with drug-loaded mesoporous carriers being developed to deliver antimicrobials without compromising bonding longevity, one of the key factors behind restoration failure[8]. Simultaneously, nano-enabled fluoride-based strategies continue to be at the heart of caries management with reports of remineralizing action of nano-silver fluoride in artificial enamel caries models supporting the role of nano formulations in lesion repair and caries arrest[9].

2. Methodology

2.1 Study design and reporting framework

It was a systematic literature review (SLR) based on the topic of drug delivery systems (DDS) in operative dentistry to manage caries and protect vital pulp, such as vital pulp therapy. The review procedure was based on a PRISMA-like identification, duplicate removal, screening, eligibility assessment, and inclusion process. In accordance with the PRISMA diagram, 163 records were identified, 16 duplicates were eliminated, 147 records were filtered, 78 full-text reports were evaluated to be eligible, and 25 studies were included in the final synthesis.

2.2 Literature search strategy

The search was done in Scopus, PubMed, Web of Science, ScienceDirect, and Google Scholar with a supplementary manual reference verification. Searching of databases gave 135 records and reference checks on manual gave 28 records, creating a total of 163 records. The title and abstract were used to screening 147 unique records after removing duplicates (n=16). Sixty-nine were filtered at the screening phase and 78 were assessed through full-text eligibility. After reading the full-text, 53 reports were eliminated and 25 studies were included.

The search terms were designed based on DDS technology and the release behavior (e.g., dental caries, secondary caries, remineralization, restorative materials, resin composite, glass ionomer, adhesive, biofilm inhibition, fluoride/calcium release, pH-triggered release, nanoparticle, mesoporous carrier, hydrogel, injectable matrix, microspheres), operative dentistry and caries outcomes (e.g., dental caries, secondary caries, remineralization, restorative materials, resin composite, glass ion Where justified by the databases, filters were used in English-language articles and a specified publication date, which also helped to cause the exclusions of the so-called temporal mismatch at full-text level.

2.3 Eligibility criteria

- Inclusion criteria

The studies were included in case they fulfilled the following conditions. First, the study had to be directly applicable to DDS or delivery-enabled biomaterials applied in operative dentistry situations to manage caries (including secondary caries control and remineralization) and/or pulp protection (including pulp capping and vital pulp therapy). Second, the article had to state a definite delivery system like nanoparticles (including mesoporous systems), hydrogels or injectable matrices, microspheres, drug-releasing cements or restorative/adhesive materials that were meant to be released therapeutically or triggered. Third, the studies needed to provide extractable results pertaining to the aim of the review including antimicrobial/biofilm results, remineralization or ion release/recharge behavior, bonding durability when DDS was included in restoratives/adhesives, or biological outcomes concerning pulp healing and regeneration. Lastly, only English-language publications were taken into consideration.

- Exclusion criteria

The studies that were not found in the scope were excluded and those that did not contain enough information to make reliable extraction and synthesis were excluded as well. The full-text exclusions were based on the categories reported in the PRISMA diagram: lack of detail (n=36), not in time with the predefined time of publication (n=13), not in English or a report on the same study (n=4). Title/abstract screening also involved the removal of records that were obviously irrelevant to DDS in operative dentistry, e.g., papers about general dentistry without a delivery system component, material science research without a therapeutic delivery/release role, and subjects not pertinent to the question of the review (e.g., AI-oriented

dentistry articles that were not relevant to caries management or pulp protection).

2.4 Study selection process

Selection of studies was done in two phases. To begin with, 147 records were screened in terms of title and abstract, which narrowed the number of records to 69 that were not relevant to the topic. Second, 78 full-text reports were evaluated using the inclusion and exclusion criteria. Fifty-three full texts were eliminated because of documented reasons, and 25 included studies were synthesized, which is in line with the PRISMA flow.

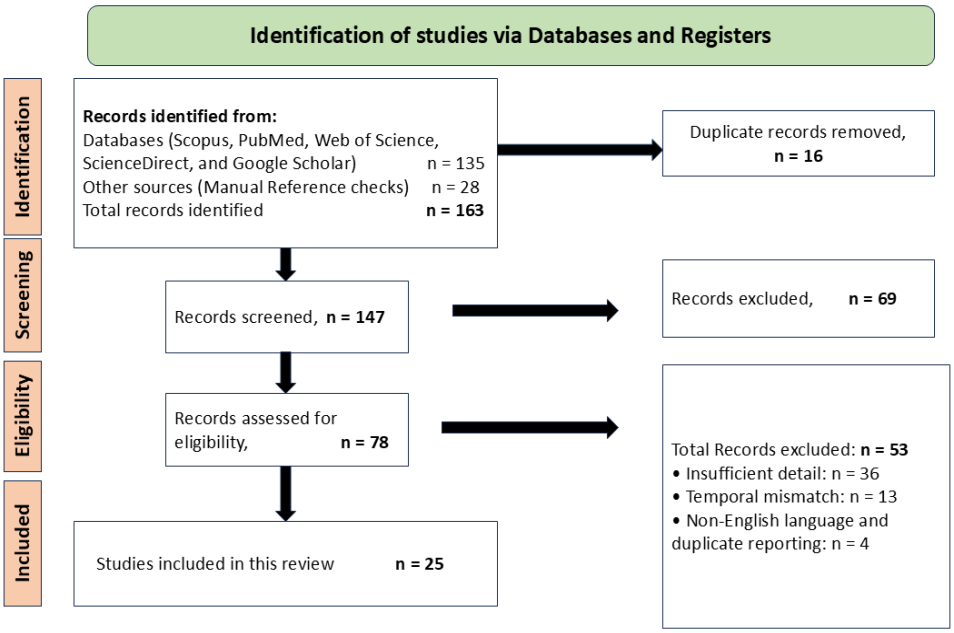

Figure 1. PRISMA flow diagram

The process of the study selection to be used in this systematic review is depicted in Figure 1. One hundred and sixty-three records were located (135 databases and 28 others). Due to the deletion of 16 duplicate records, 147 records were filtered by title and abstract and 69 were eliminated. A total of 78 full-text reports were evaluated based on eligibility and 53 were excluded because of inadequate detail (n = 36), time (n = 13), and language or duplication (n = 4). Lastly, there were 25 studies that were incorporated in the qualitative synthesis.

2.5 Data extraction

A structured template was used to extract the data to apply consistency. The information extracted consisted of publication details, study design (in vitro, in vivo/animal, clinical, or review), DDS platform (e.g., nanoparticles, mesoporous carriers, hydrogels/injectables, microspheres, drug-releasing or ion-releasing restorative systems), payload or functional agent (e.g., chlorhexidine, dexamethasone, metformin, simvastatin, silver/fluoride, bioactive ions), indication (caries management/secondary caries, reminer These data were employed to create the table of the main characters and to facilitate the synthesis of the narrative.

2.6 Risk of bias assessment

The tools used to assess risk of bias were in line with the study design. In case of the presence of randomized clinical trials, they were to be analysed with the help of RoB 2, whereas non-randomized clinical studies were to be analysed with the help of ROBINS-I. Animal studies were to be evaluated with the help of SYRCLE risk of bias approach. The review of in vitro dental materials research was evaluated in terms of a structured laboratory-quality framework that takes into consideration sample standardization, adequacy of controls, reproducibility of procedures, appropriateness of outcome measurement, and reporting completeness. AMSTAR 2 was used to appraise the methodological rigor of review articles that were included in the evidence base. Risk of bias assessment was used to interpret findings instead of being used as an exclusion criterion upon eligibility determination.

2.7 Study synthesis

Since there was heterogeneity in terms of DDS platforms, payloads and outcome measures, synthesis of evidence was performed in a narrative manner, but not via meta-analysis. The included studies were grouped into two broad themes that were in line with the goal of the review: DDS strategies to manage caries (including antimicrobial and remineralizing strategies and secondary caries prevention) and DDS strategies to protect the pulp and treat vital pulp (including injectable hydrogels, pulp-capping materials, and regenerative delivery systems). Under each of the themes, the studies were summarized based on the delivery platform and endocytes, focusing on release behavior, performance outcomes and translational relevance.

3. Results

3.1 Study selection and study characteristics

A total of 163 records were obtained in the literature search and selection process, which was a result of searching databases and checking references manually. Following the elimination of duplicates (n = 16), 147 records were sent into title and abstract screening. At this point, 69 records were eliminated since they were not within the scope of review on drug delivery systems (DDS) in operative dentistry to manage caries and/or pulp protection. A total of seventy-eight full-text reports were evaluated on the basis of eligibility and fifty-three were excluded because of the lack of methodological or outcome description, time discrepancy with the period covered in the review, and non-English language or repetitive reporting. Table 1 presents the key features of the 25 studies included in the review, such as the year of publication, the study type/design, the type of drug delivery system (DDS) platform or delivery method (e.g. nanoparticles, mesoporous carriers, hydrogels, injectable matrices, microspheres, ion-releasing restoratives), the active payload or functional component delivered, the clinical goal of the study (caries management/secondary caries prevention or pulp protection/vital pulp therapy), and the model or study setting used to assess the results.

Table 1. Key characteristics of the included studies

Ref	Year	Study type (from title)	DDS / Platform	Active agent / function	Main focus	Model/setting
10	2020	Experimental material study	CaF2 nanocomposite (ion-releasing)	Fluoride + calcium ion release + antibacterial	Caries prevention/biofilm	In vitro
11	2025	Experimental biomaterial study	Calcium phosphate pulp-capping cement	Metformin release	Pulp protection / regeneration	In vitro (DPSC-related)
12	2024	Controlled-release material study	Chitosan-coated titanium silica composite	Chlorhexidine (pH-triggered release)	Infection control (dental)	In vitro
13	2025	Review	Controlled-release nanomaterials	Antimicrobial strategies	Secondary caries	Review
14	2025	Material characterization	Drug-releasing cement	Simvastatin release	Pulp/repair-oriented cement	In vitro
15	2025	Hydrogel DDS study	β-cyclodextrin complex hydrogel	Dexamethasone	Vital pulp therapy	Likely in vitro/biological (check full text)
16	2024	Review/overview (title suggests)	Functional hydrogels	Anticaries functions	Caries treatment	Review
17	2024	Review/overview	Bioresponsive nanotechnology	Drug delivery (general)	Pediatric dental DDS	Review
18	2021	Review	Polysaccharide micro/nano DDS	Drug delivery (general)	Pediatric dentistry DDS	Review
19	2024	Review	Hydrogel composites as DDS	Drug delivery (general)	Dentistry DDS	Review
20	2020	Review	Local drug delivery systems	Drug delivery (general)	Endodontics (local DDS)	Review
21	2023	Review	Liquid crystalline systems; nanocarriers	Drug delivery (caries therapy)	Caries treatment	Review
22	2014	Experimental antimicrobial DDS	Nanoparticle-encapsulated system	Chlorhexidine	Oral biofilms	In vitro
23	2025	Review	Nanomaterial strategies	Anticaries synergy	Caries control	Review
24	2025	Review	Hydrogels	Biofilm control + remineralization	Caries prevention/treatment	Review
25	2023	Experimental	Silver nanoparticles + fluoride	Antimicrobial + fluoride effect	Root dentin caries	In vitro

26	2024	Experimental biomaterial study	Injectable chitin hydrogel	Bioactive/tannin functional	Pulp capping (inflamed pulp repair)	In vivo/biological likely (verify)
27	2024	Experimental regenerative DDS	Carbon dot nanozyme hydrogel	Antioxidative / oxidative stress regulation	Pulpitis / pulp regeneration	In vivo/biological likely (verify)
28	2023	Experimental restorative material	Bioactive nanocomposite	CaF2/CaP bioactive + antibacterial	Caries inhibition	In vitro
29	2025	In vitro study	Restorative materials (fluoride release/recharge)	Fluoride release + recharge	Anti-caries	In vitro
30	2017	Experimental	Mesoporous silica nanoparticle system	Chlorhexidine encapsulation	Anti-biofilm + material properties	In vitro
31	2014	Study/overview	Fluoride-releasing restorative materials	Fluoride release	Secondary caries inhibition	Likely in vitro/clinical mix (verify)
32	2026	Experimental regenerative DDS	Injectable GelMA hydrogel	Salvianolic acid B (anti-inflammatory)	VPT / pulpitis repair	Likely in vivo/biological (verify)
33	2024	Experimental regenerative DDS	GelMA hydrogel + Sr-bioglass	Bioactive ion delivery	Vital pulp therapy	Likely in vitro/biological (verify)
34	2026	Experimental DDS	PLGA microspheres in pulp-capping cement	Metformin (encapsulated)	Regenerative pulp capping	In vitro (DPSC-related)

In the set that was included, the evidence base was mostly experimental and materials-based, which is a characteristic of the translational aspect of DDS development in dentistry. The majority of the researches considered DDS platforms in the laboratory or preclinical conditions, analyzing release behavior, antibacterial activity, remineralization, mechanical integrity, or pulpal healing markers. A sub-group of included articles consisted of review-level syntheses, which mapped new DDS directions and identified platform trends, clinical feasibility barriers, and gaps in research. In general, the studies included were grouped into two broad areas of application that were consistent with the title of the review: DDS to manage caries (including secondary caries prevention and remineralization) and DDS to protect pulp (including pulp capping and vital pulp therapy). The characteristics table outlines the main features of the delivery platform, payload/function, main focus, and study setting of all the studies included.

3.2 Drug delivery systems for caries management

The evidence centered on caries showed that three prevailing DDS strategies were antibacterial delivery, remineralization-directed delivery and restorative materials serving as delivery reservoirs of therapy.

The field of antibacterial delivery was dominated by local delivery of antimicrobials to prevent biofilm formation and secondary prevention of caries at restoration margins. There were a number of studies that incorporated chlorhexidine into carrier systems or restorative materials to form sustained or triggered antimicrobial delivery. These were sustained-release resin-based restoratives and pH-sensitive strategies that were aimed at providing greater antimicrobial action under acidic, caries-related conditions. The theme of adhesive-interface delivery was also eminent, which is based on the clinical significance of microleakage and marginal breakdown as factors that lead to secondary caries. Research in this group generally focused on antibacterial performance as well as bonding stability or material performance, and the practical necessity to sustain adhesion with the addition of DDS functionality. The Remineralization-guided delivery was aimed at targeted delivery of mineral-promoting agents, as well as fluoride-based interventions to stimulate lesion healing or halt the demineralization process. The evidence included was nanoscale methods to deliver remineralizing complexes and nano-enabled fluoride methods used on enamel or dentin caries models. Such investigations usually measured recovery of minerals by laboratory caries models and showed that nano-enabled formulations could enhance contact, retention or activity at the tooth surface. Another similar body of evidence tested silverfluoride mixture in dentin lesions, which is an indication of dual-action approaches that combine antimicrobial action with mineral support by fluoride.

The third stream was that of ion-releasing restorative systems and bioactive nanocomposites that act as long-term therapeutic reservoirs. In these studies, restorative materials that could release fluoride and calcium ions to prevent biofilm and strengthen the protection of teeth, occasionally with recharge capacity to increase therapeutic life, were addressed. These studies usually evaluated the antibacterial action and material stability

in addition to chemical release behavior; thus, requiring DDS-based restoratives to maintain mechanical performance and dimensional stability. All of the evidence on caries-management suggests that the current DDS development is shifting beyond short-term topical delivery to restoration-based systems that offer sustained local therapeutic effect.

3.3 Drug delivery systems for pulp protection and vital pulp therapy

The pulp protection evidence focused on localized delivery, bioactive interfaces to aid in pulp healing, inflammatory regulation, and repair dentin. This field was dominated by two major types of platforms injectable/functional hydrogels and drug-releasing pulp-capping cements (including advanced sustained-release designs).

Injectable hydrogels were often placed as pulp-capping or vital pulp therapy matrices since they can create a protective barrier and deliver locally and tissue-compatible environments. Some studies outlined injectable hydrogels that had been designed with bioactive constituents that were aimed at regulating inflammation and repair in inflamed pulp situations. Such strategies as functionalization (addition of polyphenolic/tannin-based functionalities or nanozyme-based functionalities) to address oxidative stress, or a move towards biofunctional hydrogel where the hydrogel should actively regulate the microenvironment instead of passively delivery functionalities, was observed. The results of these studies generally measured reparative outcomes based on biological indicators that are applicable to pulpitis and regeneration, and material handling or stability.

A second platform group was drug-releasing pulp-capping cements. These trials added regenerative or anti-inflammatory factors to cementitious pulp-capping substances in order to combine mechanical appropriateness with treatment provision. One of the common themes was the application of small-molecule payloads in a bid to increase the dental pulp stem cell activity and repair dentinogenesis. More sophisticated designs incorporated encapsulated drug reservoirs (like polymeric microspheres) in pulp-capping cements to have a more controlled release kinetics and have an extended therapeutic exposure. Simultaneously, inclusion-complex hydrogel systems that deliver anti-inflammatory agents demonstrated a strategy of enhancing solubility and local release control and a clinically applicable delivery system. In general, the pulp-centered results reveal the evident evolution of the simplistic pulp liners into the engineered DDS matrices that combine the goals of controlled release with the regenerative design.

3.4 Emerging patterns across the evidence base

In both spheres, some cross-cutting trends were observed. First, stimuli-responsive delivery, especially pH-responsive systems aimed at producing therapeutic release in response to acidic conditions (or inflamed tissue conditions) associated with caries, was given increased attention. Second, numerous studies clearly balanced the performance of delivery with material integrity, which proved that the success of DDS in operative dentistry is determined by the ability to preserve the bonding stability, mechanical strength, and clinical handling features. Third, regenerative and inflammation-modulating payloads were also more commonly paired with injectable matrices and pulp-capping materials as the whole trend moved to biologically active restorative and pulp therapies.

3.5 Summary of results

In general, the covered articles suggest that the innovations in the field of DDS in the sphere of operative dentistry are developing in two parallel directions. In the case of caries, antimicrobial and remineralizing delivery systems that are incorporated in restoratives or adhesives or ion releasing materials are aimed at the prevention of secondary caries and in aiding mineral recovery. In the case of pulp protection, attention is paid to injectable hydrogels and drug-releasing pulp-capping systems that maintain the vitality, regulate the inflammatory process, and promote the formation of the reparative dentinogenesis. Collectively, the evidence indicates the increased role of localized DDS strategies in the connection between materials science and clinically useful caries and pulp therapies.

4. Discussion

4.1 Principal findings and interpretation

This systematic review shows a definite trend in the direction of operative dentistry with therapeutic, delivery-capable materials which do not merely replace lost tooth structure. In the evidence reviewed, drug delivery systems (DDS) were always placed to resolve two long-standing clinical issues: cariogenic biofilms and lesion activity at or around restoration margins, and pulpal vitality in deep caries patients. The data indicate that the most developed DDS directions in operative dentistry are those that can be incorporated into the most frequently used clinical agents-restorative composites, adhesives, pulp-capping agents, and injectable matrices-due to the fact that they have an immediate translational impact and can provide the delivery of agents to local sites over a longer period compared to traditional topical techniques. These themes are in line with the increasing popularity of minimally invasive approaches that involve the joint use of selective tissue ablation with biologically active substances to stabilize the processes of disease and enhance the results of long-term restoration[1].

4.2 DDS for caries management: from antimicrobial action to multifunctionality

In the case of caries management, the literature suggests that DDS development is shifting towards more balanced systems that not only promote the recovery of minerals and interface stability but also include single-

function antibacterial systems. It has been reported that nanosystems to treat caries allow a greater level of localization and retention of agents in a difficult oral environment where salivary clearance and changing pH can decrease therapeutic persistence[4]. In this respect, nanoparticle-based and nano-structured formulations offer a viable design route since they have the capability to enhance surface interaction and allow controlled or stimuli-responsive behavior. Nevertheless, there is a common translational issue that antibacterial efficacy is not likely to warrant clinical success unless it is combined with material durability and stable adhesion, especially at the toothrestoration interface. This is of clinical significance since microleakage, marginal breakdown and biofilm build-up around the edges of restorations are closely linked to secondary caries.

4.3 Adhesive-interface delivery as a high-impact direction

Introduction of DDS into adhesives and hybrid-layer interfaces seems to be among the most clinically strategic solutions to be developed in the future since the is to be provided with therapeutic agents to be released under cariogenic conditions and at the same time, the bonding durability, which directly relates to restoration longevity, must be addressed[8]. Clinically, this interface-based responsive delivery would have a potential to minimize the necessity of repeated interventions, as it would slow down the recurrence of caries and safeguard the adhesive seal. However, the majority of interface-related studies are all laboratory based and there is a difference in the measurement of the outcomes (antibacterial assays, bond strength testing, aging protocols). These systems will require standardization of testing conditions and longer-term simulation of oral stressors before they can be compared in a reliable way and transferred to clinical validation.

4.4 DDS for pulp protection: engineered matrices for inflammation control and regeneration

In pulp protection and vital pulp therapy, the evidence base is growing in Favor of DDS that serve as a protective barrier material, as well as bioactive delivery matrices. Injectable systems and pulp-capping drug releasing pulp are meant to control inflammatory micro environments, foster reparative dentinogenesis, and assist in pulp survival. An increased trend towards regenerative operative dentistry, in which preservation and repair are the aim instead of continuing to endodontic treatment, is highlighted by the development of drug-releasing hydrogels and injectable matrices. A number of the studies in this review explored hydrogel-based systems that can formulate anti-inflammatory or regenerative signals, which is indicative that local therapeutic exposure can be used to treat pulpitis-associated pathology without causing tissue incompatibility.

4.5 Translational readiness and the "materials–biology balance"

One of the lessons of this review is that translational preparedness lies in the ability to balance the delivery performance with the limitations of dental materials and clinical handling. DDS platforms should have sufficient setting behavior, mechanical strength, dimensional stability and biocompatibility and offer quantifiable therapeutic release or bioactivity. The balance is described in studies that characterize cements and pulp-capping materials which possess drug-releasing properties but it is also noted that the means of maintaining sustained and predictable release without deteriorating structural performance is complicated[23]. Moreover, regenerative-based systems, especially injectable hydrogels, should be able to exhibit biological advantage and functionality in clinical environments including moisture restraint constraints and altering cavity designs.

4.6 Strengths, limitations, and implications for future research

The review is advantageous due to a well-organized PRISMA-based workflow and a synthesis methodology that indicates platform heterogeneity in caries and pulp use. Nonetheless, there are a number of limitations on trusting generalization. One, a great part of the evidence provided is experimental and preclinical, with little direct clinical outcome reporting. Second, the quantitative synthesis is not possible in the presence of heterogeneity of DDS platforms, payloads, and outcome measures, and cross-study comparison is a difficult task. Third, most of the studies focus on evidence-based antibacterial or regenerative effects without duration checking under normal conditions of oral aging. These shortcomings indicate that the future research should focus on standardized test procedures, clinically meaningful endpoints (restoration survival and incidence of secondary caries), and improved reporting of release kinetics and biological outcomes, especially when it comes to systems with multiple functions (antibacterial + remineralizing + regenerative). New regenerative approaches, such as improved injectable matrices to be used in the pulpitis/VPT setting, can be particularly promising in case they can show reproducible reparative results and feasible handling appropriateness[32].

Conclusion

This systematic review shows that DDS innovation in operative dentistry is taking restorative care to the next level of passive repair to localized therapeutic approaches that help in caries management and maintenance of pulp vitality. Included studies, caries-oriented DDS typically integrated the antimicrobial activity with mineral support by sustained drug release, nano-enabled restorative systems, and ion-releasing remedial materials destined to inhibit the biofilm activity as well as diminish the secondary caries risk at the margins of restorations. To achieve pulp protection

and vital pulp therapy, injectable and functional hydrogels, drug-delivering pulp-capping cements, and sustained-release regenerative platforms were developed to regulate inflammation and stimulate reparative dentinogenesis, which is indicative of an increased focus on vitality-sparing and regenerative therapies of deep caries management. Although these are encouraging trends, the evidence base remains mostly laboratory and preclinical with a high degree of heterogeneity in DDS designs, release characterization, ageing studies and outcome measures which hinders direct comparison and weaken inference of long term clinical benefit. The future research must focus on standardized evaluation systems, uniform reporting of the release kinetics and biological and mechanical outcomes and the design of the translational and clinical studies that can be used to evaluate the longevity of the restoration, secondary caries, and pulp vitality over significant post-interventions. To conclude, DDS can be very beneficial to reinvent operative dentistry by incorporating prevention, repair, and regeneration into the mainstream restorative practice.

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