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Nano-Enhanced Irreversible Hydrocolloid Impression Materials: A Systematic Review of Mechanical, Dimensional, and Antimicrobial Outcomes in Prosthodontics

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Conflict of interest: Nil

Abstract

Background/Introduction: Irreversible hydrocolloids, a commonly used preliminary impression material in routine dental practice, having limited use for final impressions because of its' poor dimensional stability, low tear strength, and susceptibility to microbial contamination. Nanoparticle incorporation such as silver (AgNPs) and zinc oxide (ZnO NPs) has been studied since long to enhance the mechanical and biological properties of these materials.

Aim/Objectives: The aim of this systematic review is to evaluate the benefits of nanoparticle incorporation in hydrocolloid impression materials on three key parameters namely mechanical properties, dimensional stability, and antimicrobial efficacy.

Material and Method: A comprehensive search across PubMed, Google Scholar, and EBSCO was conducted for in-vitro studies from 2010 to 2024 written in English language only. Search terms used were "alginate," "silver nanoparticles," "zinc oxide nanoparticles," "impression material," "mechanical properties," "dimensional stability," and "antimicrobial activity." Studies were selected using the PICOS framework. The methodological quality of the data obtained was assessed using the QUIN tool.

Result: Total number of studies meeting inclusion criteria were seven, out of which five studies evaluated Silver incorporation (concentration 0.5–5 wt%), and two investigated Zinc Oxide (concentration 5–15 wt%). Silver nanoparticle's improved the tear strength, elastic recovery, and antimicrobial activity without adversely affecting handling characteristics at low concentrations. Dimensional stability and antifungal efficacy was enhanced by zinc oxide nanoparticles while elation time

and flow properties were affected at higher concentrations of nanoparticle. QUIN tool assessment identified one study as low-risk and six as medium-risk.

Discussion: While nanoparticle incorporation demonstrates promising antimicrobial and mechanical benefits, the predominantly in vitro evidence base and methodological heterogeneity across studies limit definitive clinical translation at this stage underscoring the need for more rigorous, standardized research protocols.

Conclusion: Incorporation of nanoparticles like Ag and ZnO, improves the mechanical performance, dimensional stability, and antimicrobial efficacy of hydrocolloid impression materials at different concentration. Standardized in vivo and clinical studies are still necessary before routine clinical adoption is recommended.

Keywords: Silver nanoparticles, Zinc oxide nanoparticles, Irreversible Hydrocolloid, Impression material.

Introduction

Irreversible hydrocolloid is one of the most commonly used impression material in prosthodontics due to low cost, ease of manipulation, hydrophilic nature, and considerably less setting time [1–3] that makes it a favorable choice. It is commonly used for record preliminary impressions and certain removable prosthodontic procedures. Conventional irreversible hydrocolloid has several limitations stemming from poor dimensional stability, low tear strength, and high susceptibility to microbial contamination [4,5]. Furthermore, syneresis and imbibition causes dimensional changes that compromise the accuracy of impressions, if pouring is delayed [6]. The risk of cross-contamination during clinical and laboratory procedures is heightened if proper disinfection is not strictly followed which is difficult in routine practice [7]. It is therefore not recommended for use as a final impression material.

Recent advancements in nanotechnology have enabled the incorporation of nanoparticles into dental materials to improve their shortcomings. They inhibit unique physico-chemical and biological characteristics because of their high surface area-to-volume ratio which makes them effective for reinforcement in dental materials [8–12]. Among these, silver (AgNPs) has shown promising broad-spectrum antimicrobial activity against oral pathogens such as Streptococcus mutans, Candida albicans, and Enterococcus faecalis [13–17]. Evidence also indicates that optimal concentrations of AgNPs can enhance the tear strength and elastic recovery of irreversible hydrocolloid without adversely affecting handling properties [18–20].

Zinc oxide nanoparticles (ZnO NPs) have shown antifungal activity, biocompatibility, and ability to improve dimensional stability of irreversible hydrocolloid impression material [21–26]. Nanoparticle incorporation into impression material may reduce dependence on conventional chemical disinfection techniques, which is known to affect impression accuracy of alginates [27–30]. Evidence from literature which is currently available is fragmented because of variations in: nanoparticle type, concentration, synthesis method, and testing protocols across all studies [31–37].

This systematic review aims to evaluate the effect of incorporation of nanoparticles such as Ag and ZnO on the mechanical properties, dimensional stability, and antimicrobial efficacy of irreversible hydrocolloid impression materials. The review was conducted according to the PRISMA 2020 guidelines, and the risk

of bias assessment of all included studies was assessed using the QUIN tool [8,9].

Material and Method

Articles in this systematic review were searched and screened in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure replicability in study selection, data extraction, and reporting [1]. The review was designed using PICOS framework with the main focus on synthesizing evidence from in vitro studies that evaluated effect of nanoparticle incorporation into irreversible hydrocolloid impression materials across three parameters.

Eligibility Criteria (PICOS Framework)

This review followed the PRISMA 2020 guideline. PICOS model was used to define the eligibility criteria.

PICOS Component	Description
Population (P)	**Alginate impression materials** used in **dental applications**.
Intervention (I)	**Incorporation of nanoparticles** (*e.g., Silver Nanoparticles (AgNPs), Zinc Oxide Nanoparticles (ZnO NPs)*) into alginate impression materials.
Comparison (C)	**Conventional alginate impression materials** without nanoparticle incorporation or those modified with other agents (eg. chlorhexidine (CHX), povidone-iodine, or other antimicrobial agents.)
Outcome (O)	- **Mechanical Properties** (*tear strength, elasticity, gelation time, dimensional stability*).
	- **Dimensional Stability** (*volumetric stability, shrinkage, and surface detail reproduction*).
	- **Antimicrobial Efficacy**
Study Design (S)	**In-vitro experimental studies** evaluating mechanical, dimensional, and antimicrobial properties of nanoparticle-modified alginate impression materials.

Inclusion criteria

1. Studies evaluating the incorporation of nanoparticles into irreversible hydrocolloid impression materials.
2. Studies assessing at least one of the following outcomes: mechanical properties, dimensional stability, or antimicrobial efficacy.
3. In-vitro or clinical studies published in English.
4. Comparative analysis with control (unmodified) alginate.

Exclusion criteria

1. Reviews, case reports, letters to editors, or conference abstracts or studies lacking sufficient data
2. In vivo or animal studies
3. Studies lacking a comparator group

Search Strategy

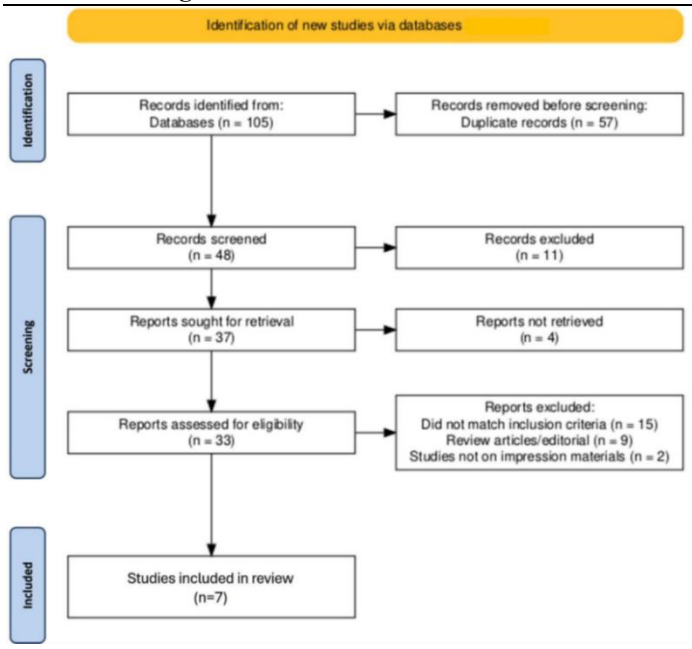
A search across various search engines like PubMed, Google Scholar, and EBSCO was done to find studies that were published from January 2010 to March 2024. Terms such as ("Nanoparticles" OR "Silver Nanoparticles" OR "AgNPs") AND ("Alginate" OR "Dental Impression Material") AND ("Mechanical Properties" OR "Dimensional Stability" OR "Antimicrobial Efficacy") were used for the search.

To improve comprehensiveness, same Boolean operators were used in each database. In addition, a manual search of the reference lists of selected studies and relevant reviews was performed to retrieve missed articles.

Study Selection

After examining the titles and abstracts of unique records to determine whether they met eligibility criteria, full-text articles were obtained and reviewed for final inclusion in the review.

A total of 105 records were identified through database searches; duplicates were removed, 48 records were screened based on titles and abstracts, 11 studies were excluded and 37 articles were obtained. Full-text reviews of 4 articles couldn't be found, and 26 were excluded during full-text reviews. 7 studies qualified for a systematic review. Other articles obtained from these studies were used in discussion section of the manuscript.



Data Extraction

A standardized form was used to extract data from each study, including:

1. Author, publication year, and study design
2. Type, concentration and synthesis method of nanoparticles used.
3. Control group (alternative antimicrobial agents).
4. Outcome measures assessed: Mechanical properties, dimensional stability, and antimicrobial efficacy.
5. Key findings and statistical significance: The data was synthesized narratively and, wherever possible, comparisons between nanoparticle-incorporated alginate and conventional alginate were performed. Wherever possible, quantitative values for improvement or deterioration in properties were recorded and compared across studies.

Risk of Bias Assessment

The Quality Index for In Vitro Studies (QUIN) was used to assess the risk of bias for each of the seven included in vitro studies. The QUIN scoring system was developed by Sheth et al. (2) and validated for in vitro laboratory studies.

Each study is evaluated based on 12 key criteria, each assessing a different aspect of study design, execution, and reporting:

QUIN Criteria and Assessment Parameters

1. Clearly stated aims/objectives: Study should define its aims and follow them consistently.
2. Detailed explanation of sample size calculation: Method of sample size determination, including software, formula, and parameters used.
3. Detailed explanation of sampling technique: Description of population selection, inclusion/exclusion criteria, and sampling technique.
4. Details of comparison group: Specification of control groups (e.g., positive control, negative control, standard treatment).
5. Detailed explanation of methodology: Standardization of procedure and use of universal standards (if applicable).
6. Operator details: Number of operators, training details, and inter-operator calibration.
7. Randomization: Details on sequence generation and allocation concealment.
8. Method of measurement of outcome: Clarity on procedure and choice of outcome measurement method, with standardization.
9. Outcome assessor details: Training and calibration of assessors, with inter-assessor reliability.
10. Blinding: Description of blinding for operators, assessors, and statisticians.
11. Statistical analysis: Software used and methods applied for data analysis.
12. Presentation of results: Clear alignment of results with study aims, with well-structured tables and baseline data.

Criteria No.	Year	1	2	3	4	5	6	7	8	9	10	11	12	Total	Final Score (%)	Risk Status
Ginjupalli et al.[1]	2016	2	2	1	2	2	0	0	1	2	0	2	2	14	58.33	Medium risk
Nia et al.[2]	2018	2	2	1	2	2	1	0	2	2	0	2	2	18	75	Low risk
Omidkhoda et al.[3]	2019	2	2	1	2	2	0	0	1	1	0	2	2	16	66.67	Medium risk
Singer and Bourauel[4]	2023	2	2	1	2	2	0	0	2	1	0	2	2	14	58.33	Medium risk
Singer et al.[5]	2023	2	2	0	1	2	2	0	0	1	0	2	2	14	58.33	Medium risk
Bendary et al.[6]	2024	2	2	1	2	2	1	0	2	1	0	2	1	14	58.33	Medium risk
Al-Nema et al.[7]	2024	2	2	0	1	2	2	0	1	1	0	2	2	12	50	Medium risk

Each domain is scored on a scale of 0 (not reported), 1 (partially reported), or 2 (fully reported), generating a total score expressed as a percentage.

Risk classification:

>70% = Low risk

50–70% = Medium risk

<50% = High risk

Of the seven studies included:

1 study was classified as low risk (score >80%), 6 studies were medium risk, mainly due to:

Absence of sample size calculations

Lack of blinding or randomization

Poor documentation of nanoparticle synthesis methods

Despite methodological variation, outcome reporting was generally clear, and control groups were consistently used.

Results

This review extracted data from 7 in vitro studies that studied the incorporation of silver (Ag) or zinc oxide (ZnO) nanoparticles into irreversible hydrocolloid impression materials, assessing their effect on mechanical properties, dimensional stability, and antimicrobial efficacy. All included studies compared nanoparticle-enhanced alginate with commercially available conventional alginates.

Mechanical Properties

Two of the seven studies evaluated mechanical properties with main focus on tear strength, elastic recovery, and flowability.

AgNPs at concentrations of 0.5% to 2% considerably improved tear strength and elastic recovery without compromising gelation time or clinical handling [1,9]. Ginjupalli et al. [1] reported that 1% AgNPs increased tear strength by 35%, Singer and Bourauel [4] found they enhanced tear strength while Bendary et al. [6] found that elastic recovery improved by 22% in AgNP-modified groups.

Gelation time and flow was affected at higher concentrations of more than 2% [8,10,27]. Alginates containing AgNPs at a concentration of more than 5% showed diminished flowabilty according to ISO 4823 criteria, as excessive filler content causes an increase in viscosity [11].

ZnO NPs was used in one study at concentrations ranging from 5–15%. Al-Nema et al. [7] reported only marginal enhancement in tensile strength (~9%) at 10% ZnO NP concentration while compromising flow and handling.

Supporting literature selected show that AgNPs because of their smaller particle size and surface interaction are more efficient than ZnO NPs when added to irreversible hydrocolloid materials [18,19].

Dimensional Stability

Of the selected studies, only 3 evaluated dimensional changes, assessed as linear shrinkage, volumetric loss, or flow behavior over time.

In AgNP-enhanced alginates, dimensional stability met ISO 1563 standards at concentrations up to 2%, above which shrinkage increased due to interference with water-holding capacity [1,6]. Bendary et al [6] found that at a concentration of 2%, volumetric shrinkage remained <1.2% after 60 minutes, compared to 2.1% in unmodified alginate.

In contrast, ZnO NPs significantly improved dimensional retention, especially at higher concentrations (≥5%). Al-

Nema et al. [7] found that alginate containing 10% ZnO NPs had 30% lower linear contraction within 60 minutes than the control group.

In conclusio, ZnO NPs are better at maintaining dimensional stability than Ag NPs, which can be beneficial during delayed pouring because of laboratory transfers.

Antimicrobial Efficacy

Antimicrobial performance against commonly encountered oral pathogens was studied in all of the studies. Tests such as agar diffusion, zone of inhibition, and colony-forming unit (CFU) reduction was used for comparing performance.

AgNP-incorporated alginates demonstrated broad-spectrum antibacterial activity against S. aureus, E. faecalis, E. coli, and Candida albicans [1,5,6,7]. Ginjupalli et al.[1] found a 95% reduction in CFU counts with 1% AgNP-enhanced alginate compared to control. Singer et al.[2] observed larger zones of inhibition with 2% AgNPs than with chlorhexidine-treated alginate, suggesting superior or equivalent disinfection potential.

ZnO NPs were less potent against gram-negative bacteria but exhibited notable antifungal efficacy against C. albicans. Al-Nema et al.[7] reported significant inhibition zones at concentrations of 10–15%.

Overall, AgNP-enhanced materials were found to show better antimicrobial efficacy comparable to chlorhexidine and retained antimicrobial actions for up to 60 minutes [2,35].

Outcome Parameter	Effect of Silver Nanoparticles (AgNPs)
Mechanical Properties	• Increased tear strength & elastic recovery at 0.5–5% • Higher concentrations ↑ gelation time & deformation • Better flexibility vs. ZnO • Handling compromised at high doses
Dimensional Stability	• Mixed results: minimal change in some studies • Shrinkage at higher concentrations • ISO 1563 accuracy maintained
Antimicrobial Properties	• Strong broad-spectrum activity • Effective against S. aureus, E. coli, Candida spp. • 0.1–0.2% ≈ 0.2% CHX • Higher doses ↑ antimicrobial effect but ↓ handling

Outcome Parameter	Effect of Zinc Oxide Nanoparticles (ZnO NPs)
Mechanical Properties	• No significant mechanical improvement • AgNPs perform better mechanically
Dimensional Stability	• ZnO ≥5% improves dimensional stability • Better thermal stability and minimal distortion
Antimicrobial Properties	• Effective antibacterial & antifungal effects ≥5% • MBC/MFC ~10% • Higher doses improve efficacy but affect handling

Discussion

The studies included in this systematic review show that incorporating nanoparticles into alginate impression materials can improve several clinically relevant properties, although the extent of improvement depends largely on the nanoparticle type and concentration used. Silver nanoparticles were investigated more frequently than zinc oxide nanoparticles, and most authors reported favorable effects on both antimicrobial activity and mechanical behavior [1,4,7]. Improvements in tear strength and elastic recovery were commonly observed when AgNPs were added in lower concentrations, particularly around 0.5–2%. This may be related to the nanoparticles' ability to occupy spaces within the alginate matrix and strengthen intermolecular interactions. Similar strengthening effects of AgNPs have also been described in other dental materials, including acrylic resins and restorative composites [16–18].

However, the findings were not entirely consistent across all studies. A few investigations noted that increasing nanoparticle concentration beyond an optimal range

negatively affected flow and gelation characteristics [8,27]. Excess nanoparticle loading may alter water distribution within the hydrocolloid structure, leading to increased viscosity and reduced handling efficiency. Therefore, while nanoparticles appear beneficial, the concentration used becomes clinically important.

ZnO nanoparticles showed comparatively less effect on mechanical reinforcement but appeared to improve dimensional stability more effectively [7,22]. This is clinically relevant because dimensional changes remain one of the major limitations of alginate impressions. Reduced shrinkage and improved stability may be explained by stronger ionic interactions occurring between zinc ions and alginate chains, helping maintain the gel structure over time. Similar observations have been reported in ZnO-containing hydrogel systems used in biomedical applications [14,15].

The antimicrobial findings were among the most significant outcomes reported in the included studies. AgNP-modified alginates demonstrated activity against organisms commonly associated with cross-contamination in dentistry, including S. aureus, E. coli, E. faecalis, and Candida albicans [1–3]. The antimicrobial action of silver nanoparticles is believed to involve membrane disruption, oxidative stress, and interference with microbial metabolic pathways [13,16,30]. ZnO nanoparticles also demonstrated antimicrobial effects, particularly against fungal species [7,11]. Such modifications may reduce dependence on conventional chemical disinfection procedures, which themselves can affect impression accuracy if improperly performed [27–29].

Despite these promising findings, several limitations were identified. All included studies were in vitro, and therefore clinical extrapolation should be approached cautiously. Considerable heterogeneity existed between studies in terms of nanoparticle synthesis, particle size, concentrations, and testing protocols. In addition, most studies demonstrated moderate methodological quality according to QUIN assessment because details regarding randomization, sample size calculation, and blinding were often unclear [8,9]. Evidence regarding long-term biocompatibility and cytotoxicity also remains limited.

Routine use of nanoparticle-enhanced alginate impression materials cannot be recommended until extensive research is done with standardized methodologies and long-term in vivo studies evaluating the toxicity levels. This would help establish clearer guidelines regarding their safe and effective use in prosthodontic practice.

Conclusions

Within the limitations of this systematic review, nanoparticle incorporation appears to improve the overall performance of alginate impression materials. Silver nanoparticles demonstrated greater influence on antimicrobial activity and mechanical properties, whereas zinc oxide nanoparticles contributed more to dimensional stability and antifungal effects [1,4,7,22]. These findings suggest that nanoparticle-modified alginates may help overcome some of the inherent shortcomings of conventional alginate.

At the same time, nanoparticle concentration remains critical, since excessive incorporation may negatively influence handling and setting characteristics [8,27]. Because the available evidence is limited mainly to in vitro investigations, further clinical studies are still required. Additional research focusing on biocompatibility, long-term stability, and standardized testing protocols will be essential before these materials can be adopted widely in routine dental practice.

List of abbreviations

AgNPs – Silver nanoparticles

ZnONPs – zinc oxide nanoparticles.

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