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Modern Polymer Systems in Nail Services: Acrylic Versus Hard Gel

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Abstract: The article presents a comprehensive comparison of two predominant platforms used in contemporary nail services: classical monomer–polymer acrylate systems and UV-cured hard gels. The aim of the study is to conduct an integrated comparative analysis of the physicochemical, mechanical, and toxicological profiles of traditional acrylic systems and modern UV-cured hard gels, providing an evidence-based assessment of their effects on the integrity of the natural nail structure and the safety of their use in salon practice. The methodological framework includes a systematic review of interdisciplinary sources in polymer chemistry and physics, materials science, dermatology, and occupational hygiene, as well as a critical analysis of regulatory documents; emphasis is placed on reproducible selection criteria and comparability of metrics. The analytical block is structured around physicochemical determinants: monomer composition, crosslinking and kinetics/degree of conversion, post polymerization shrinkage, residual monomer fraction, and molecular weight distribution. These parameters are correlated with performance characteristics of the coatings, including elastic modulus and viscoelastic response, adhesion to the keratin substrate, wear and impact resistance, and resistance to wetting/drying cycles. The study demonstrates that UV-cured gels, by virtue of a softer mechanics profile (lower effective modulus and better tolerance to shear deformation), exhibit high biomechanical compatibility with the natural nail plate, reducing local stresses and the likelihood of microcrack formation. Toxicological assessment revealed a substantial differentiation of occupational risks: for acrylate monomers, inhalation exposure to volatile organic compounds and dust aerosols during filing predominates, whereas for gel systems the key factor is control of UV exposure dose and ensuring sufficient depth/completeness of cure to minimize residual monomer. When protocols for safe use are followed (local exhaust ventilation, personal protective equipment, correct photopolymerization, and a lamp replacement schedule), UV-cured hard gels appear to be a more biocompatible and mechanically sparing technology that helps preserve the structural integrity of the nail plate. The findings have practical significance for nail technicians (selection of materials and operating parameters), formulation technologists (optimization of formulations for target mechanical and toxicological profiles), instructors of specialized programs (updating training modules on safety and materials science), and dermatologists (clinical prevention and management of contact reactions).

Keywords: hard gel, acrylic system, polymerization, nail services, elastic modulus, allergic contact dermatitis, methacrylate's, workplace safety, nail biomechanics, polymer chemistry.

Introduction

The evolution of technologies in nail services is closely determined by advances in polymer chemistry. For decades, the industry gold standard for modeling and reinforcement has been two-component acrylic systems: a combination of liquid monomer and polymer powder that polymerize via a radical mechanism [1]. Their sustained market success has been explained primarily by the high load-bearing capacity and wear resistance of the formed coating. The emergence of photopolymerizable UV gels, with controlled initiation of curing, a different network architecture, and distinct rheological characteristics, marked a qualitative technological shift. Today there is a stable reorientation of both consumer and professional practices toward gel systems, which necessitates an impartial comparison of their performance and hygienic properties with traditional acrylates [2, 3].

The key scientific issue fueling professional discussions concerns the long-term impact of these polymer systems on the structures of the nail unit (nail plate, bed, matrix). The common empirical premise that acrylic coatings more often lead to degradation of the plate, whereas hard gels allegedly preserve its condition, requires rigorous verification. The research deficit lies in the absence of comprehensive interdisciplinary studies that would relate fundamental physicochemical parameters (degree of crosslinking, elastic modulus, shrinkage stresses, residual monomer, volatility of components) and mechanical characteristics of coatings to clinical outcomes for nail tissue, as well as to occupational risks for technicians (aerosol exposure, sensitization, cumulative loads).

The aim of the study is to conduct a comprehensive comparative analysis of the physicochemical, mechanical, and toxicological profiles of traditional acrylic systems and modern UV-curable hard gels, providing a scientifically grounded assessment of their effects on the preservation of the natural nail structure and on the safety of their use in salon practice.

The working hypothesis is that UV-curable hard gels, due to the oligomeric nature of their precursors, lower volatility of constituent components, reduced propensity to generate high shrinkage stresses, and increased functional elasticity of the coating, demonstrate greater biocompatibility and mechanical gentleness with respect to the nail plate compared with acrylates. As a consequence, there is a higher likelihood of preserving the structural integrity of the natural nail during prolonged wear and correction cycles.

The scientific novelty of the work lies not in a simple comparison of ingredient toxicity, but in the systematization of interdisciplinary data and their integration into a concept of biomechanical compatibility of coating–substrate.

Materials and methods

The study was conducted in the logic of a systematized review with elements of comparative analysis. To achieve the research objective, a targeted integration of empirical and theoretical data from adjacent disciplines — polymer chemistry, materials science, toxicology, clinical dermatology, and occupational hygiene — was carried out. This interdisciplinary synthesis made it possible to link levels of description from molecular architecture and curing kinetics to clinical and occupational hygiene effects for humans, forming a consistent picture of the functioning of the systems under consideration.

Prioritization of sources was implemented as follows.

Primary sources: original studies from Scopus, Web of Science, and PubMed/PMC devoted to the physicochemical and mechanical parameters of polymer coatings, as well as the clinical and toxicological consequences of their use.

Secondary sources: regulatory documents and analytical reports of authoritative governmental and supra-departmental bodies, primarily the Occupational Safety and Health Administration (OSHA) and the US Centers for Disease Control and Prevention (CDC), containing systematized data on occupational risks and chemical hazards in the nail salon industry.

Comparative assessment was conducted within a pre-specified matrix of four analytical axes applicable to each polymer system:

- Physicochemical characteristics. A detailed analysis was performed of composition (monomers, oligomers, initiators), the mechanism and kinetics of polymerization, the profile of volatile components, and the thermal effect (exothermicity) of the process, including possible migration of unreacted low-molecular-weight fragments.

- Mechanical and performance properties. The adhesion-cohesion balance to the nail plate, elastic modulus (stiffness/flexibility), hardness, wear resistance (including abrasion resistance), and preservation of aesthetic parameters — gloss and color stability under typical household stressors (moisture, temperature, friction) — were evaluated.

- Safety profile and biocompatibility. Toxicological characteristics of individual ingredients, scenarios of inhalation exposure to volatile organic compounds (VOCs) in the salon environment, and sensitizing potential with emphasis on the risk of allergic contact dermatitis (ACD) via a delayed-type hypersensitivity mechanism were considered.

- Effects on the nail plate. Mechanisms of potential damage were analyzed — from biomechanical factors during wear (mismatch between the elastic moduli of the coating and keratin, local stress concentrations) to the chemical aggressiveness of preparation, application, and removal procedures, including abrasive treatment and the use of solvents.

Such use of sources ensures comparability of results across different polymer systems and makes it possible to trace causal relationships from molecular parameters to clinically significant outcomes.

Results and discussion

Key differences in application behavior and risk profiles of acrylic and UV gel systems are determined by their molecular architecture and the mode of initiation of radical polymerization. In other words, the monomers and oligomers from which the material is assembled, and what triggers the growth of polymer chains, predetermine both processability and toxicological and hygienic characteristics of the coating.

Acrylic materials are the classical two-component powder–liquid system. The liquid phase is typically ethyl methacrylate (EMA), which has replaced the more reactive and, in some countries, restricted methyl methacrylate (MMA) [12]. The powder is finely dispersed PMMA with a bound initiator (usually benzoyl peroxide), whereas the monomer liquid contains a tertiary amine activator. When the powder is wetted by the liquid, chain free-radical polymerization is initiated, accompanied by a noticeable exothermic effect and evaporation of part of the monomer. Because of the high volatility of EMA, a significant inhalation burden is created for the technician and nearby individuals [4, 12]. An additional technological feature is the absence of a pause button: after mixing the components, the composition's pot life is limited, which requires fast and confident work; otherwise, the risk of technological defects increases.

UV-curable gels, by contrast, are supplied as single-component compositions based on oligomers (often urethane acrylates) with terminal acrylate groups that enable crosslinking upon irradiation [5]. To achieve the required consistency, reactive diluents are introduced into the mixture, typically HEMA or HPMA, and radical initiation occurs via photoinitiators under UV/LED radiation of a specified wavelength. This photoregulated mechanism provides a technological advantage: polymerization starts only at the operator's command (when the material is placed in the lamp), which affords a practically unlimited modeling window and reduces inhalation exposures due to the lower volatility of the components compared with EMA. However, the kinetics of photopolymerization are sensitive to oxygen: surface inhibition leads to the formation of a tacky dispersion layer of unreacted oligomers/monomers, which is regarded as the main risk factor for contact skin sensitization [6, 9] (fig.1).

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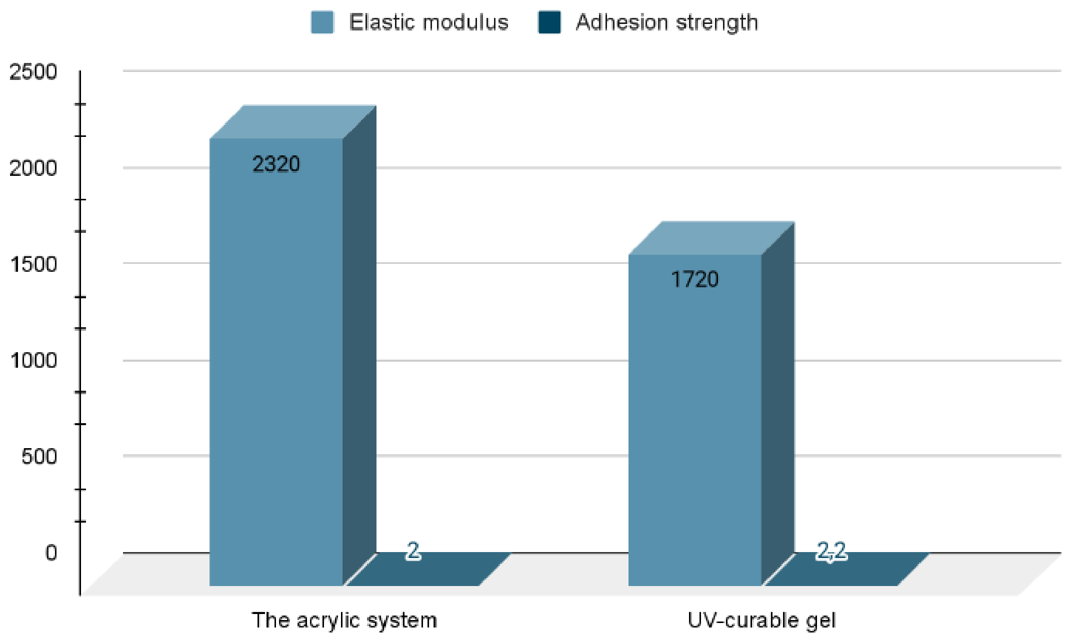

Fig. 1. Comparative diagram of the modulus of elasticity and strength (compiled by the author based on [5, 6, 9, 12]).

Consequently, the controllability of photopolymerization in gel systems is not merely a convenient technological mode but the principal determinant of the process's industrial hygiene. The ability to start and stop curing in response to a signal radically reconfigures the hazard profile: the dominant inhalation exposure pathway, typical of acrylate systems with volatile monomers, is replaced by a spatially confined contact risk at the coating surface. The latter is amenable to effective engineering and procedural neutralization: appropriate selection of irradiation regime and achievement of complete cure, careful and timely removal of the dispersion (oxygen-inhibited) layer, as well as adherence to standards of skin barrier protection and workplace hygiene. Taken together, this shifts the risk from diffuse and difficult to control to manageable and minimizable. Below, Table 1 presents a comparative characterization of the chemical composition and the polymerization process.

Table 1. Comparative characteristics of the chemical composition and polymerization process (compiled by the author on the basis of [6, 8, 10]).

Parameter	Acrylic system	UV-curable gel system
Main component	Polymethyl methacrylate (powder)	(Meth)acrylate oligomers (urethane, polyester)
Reactive diluent	Ethyl methacrylate (liquid)	(Meth)acrylate monomers (HEMA, HPMA, IBOA)
Initiator	Benzoyl peroxide (chemical)	Photoinitiators (α-hydroxyketones, acylphosphine oxides)
Polymerization type	Free-radical, chemical initiation	Free-radical, photoinitiation (UV/LED)
Volatility of components	High (EMA monomer)	Low
Cure control	Absent (reaction starts upon mixing)	Complete (reaction starts under light)

Exothermic reaction	Pronounced, uncontrolled	Moderate, depends on lamp power and layer thickness
Key residues	Unreacted monomer within the polymer bulk	Dispersion (tacky) layer on the surface

The mechanical behavior of a polymer coating determines not only its service life but also the nature of its interaction with the tissue of the natural nail. The key quantity is the Young's modulus, which reflects the linear elastic stiffness of the material. The nail plate is a comparatively compliant keratinous composite; its effective Young's modulus is ≈2320 MPa [5], that is, noticeably lower than that of most rigid polymer networks.

Acrylate (acrylic) systems upon curing form a highly crosslinked glassy structure with a large E. Such an architecture imparts high hardness to the coating; however, it is accompanied by low deformability and low fracture toughness. A pronounced compliance gradient arises between the rigid coating and the flexible nail substrate: during bending of the nail plate and/or impact loading, the neutral axis shifts, and shear and peel stresses concentrate at the coating–nail interface. According to the mechanics of thin films, the maxima of such stresses localize at edges and defects, where nucleation of microcracks, initiation of interfacial weakening, and subsequent delamination are likely. As a result, part of the load is transmitted into the thickness of the nail plate, provoking its microdamage and detachment of the coating (see Fig. 2) [7, 16].

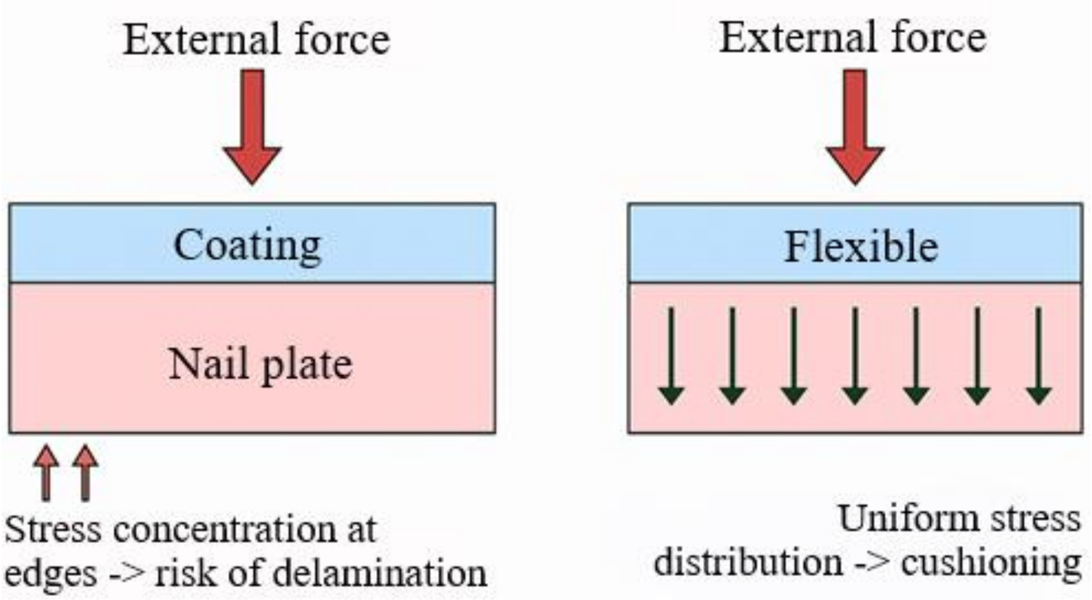

Fig. 2. Schematic representation of the distribution of stresses in the nail plate (compiled by the author based on [7, 16]).

Gel compositions are three-dimensionally crosslinked networks of long, mobile oligomeric segments, which shifts their elastic–deformation characteristics toward greater compliance: a typical Young's modulus lies at a comparatively low level, on the order of E = 200–2000 MPa [5]. This soft–stiff architecture reduces the modulus contrast with the keratinous substrate of the nail plate, enables the coating to follow its microrelief and curvature without residual stresses, and redistributes local stress concentrators. As a result, the probability of crack initiation at the interface decreases, as do the number of delaminations and the risk of microtrauma to the natural nail.

Adhesion to the nail plate remains a key parameter. In acrylic technologies it is often maximized through acid primers based on methacrylic acid, which chemically etch the substrate while simultaneously dehydrating it and partially denaturing the keratin matrix [12]. This approach provides pronounced microrough anchoring but increases the aggressiveness of the preparation. In gel systems, bond strength is achieved via a combined mechanism: mechanical interlocking with the pretreated surface and the formation of chemical bonds, including radical and hydrogen interactions, with the involvement of less aggressive acid-free primers. Quantitatively, the adhesive strength of modern coatings is on the order of 1,5–2,5 MPa, which is sufficient to withstand service shear and peel loads without transitioning to brittle failure of the interface [8]. With proper preparation, a cohesive rather than adhesive failure mode is more commonly observed, which further confirms the adequacy of adhesion [3, 9].

From aesthetic and performance standpoints, gel coatings demonstrate better retention of optical properties: stable gloss and a lower propensity for yellowing compared with acrylates, which are characterized by color drift over time. Wear resistance, however, is a formulation-controlled parameter and is tightly linked to the functionality of the monomer composition: increasing the fraction of multifunctional acrylates increases crosslink density and resistance to abrasive wear. Thus, inclusion of the trifunctional monomer TMPTMA provides the highest anti-abrasive resistance (gloss retention at the level of 76 GU upon completion of the tests), which is combined with long-term color purity of the coating [12]. At the same time, an optimal balance between network density and its segmental mobility makes it possible to maintain both wear resistance and crack resistance, minimizing the risk of delamination under real-world wear conditions.

Safety profile evaluation is a central criterion when comparing polymer technologies. According to OSHA and CDC reports, the use of acrylic systems is characterized by a substantially higher occupational risk because of the high volatility of the EMA monomer and the presence of other VOCs in formulations (e.g., toluene) [12]. Inhalational exposure to these substances is associated with a wide spectrum of adverse effects: from irritation of the respiratory mucosa, headache, and dizziness to chronic toxic injuries affecting the bronchopulmonary system (including occupational asthma), liver, kidneys, and central nervous system; reproductive toxicity is also possible [12]. To reduce exposure, engineering source control is required — local exhaust (source-capture) integrated into the work surface, which in many jurisdictions is codified as a mandatory requirement [13, 14].

Gel systems, in contrast, due to the low volatility of their main components, create a less hazardous aerosol environment in the workplace. However, the contact route of exposure becomes dominant. Allergic contact dermatitis (ACD) is the most frequent adverse event for both technologies, caused by exposure of the skin to unreacted sensitizing monomers [3, 11]. Among the most significant allergens, HEMA and 2-hydroxypropyl methacrylate (HPMA) consistently appear [3]. In acrylic systems, the contact risk arises primarily during handling of the liquid monomer; in gels, when material contacts the skin before polymerization is complete, or upon contact with the dispersion (sticky) layer thereafter. It has been demonstrated that even fully cured no-wipe gels can contain residual amounts of monomers (for example, HEMA at 139 µg/g) [11]. Therefore, it is critically important to strictly follow safety procedures, use personal protective equipment (including nitrile gloves), and completely eliminate any contact of uncured material with the skin regardless of the system used. In Table 2, chemical hazards and associated health risks will be described according to OSHA.

Table 2. Major chemical hazards and associated health risks according to OSHA (compiled by the author on the basis of [3, 8, 11, 15]).

Chemical agent	System(s)	Documented health risks
Ethyl methacrylate (EMA)	Acrylic system	Occupational asthma; irritation of eyes, skin, nose, mouth; difficulty concentrating; potential fetal harm during pregnancy.
Methacrylic acid	Acrylic system (primer)	Skin burns; irritation of eyes, skin, respiratory tract; at high concentrations may cause breathing difficulties.
Toluene	Acrylic system, lacquers	Dryness and cracking of the skin; headaches, dizziness; irritation of eyes, nose, lungs; liver and kidney damage; fetal harm.

Dibutyl phthalate (DBP)	Lacquers, sometimes acrylics	Nausea; irritation of eyes, skin, respiratory tract; possible reproductive harm.
Formaldehyde	Lacquers, hardeners	Breathing difficulty, asthmatic attacks; allergic reactions; irritation of eyes, skin, throat; known carcinogen.
(Meth)acrylate monomers (general, incl. HEMA)	UV gel system	Allergic contact dermatitis (principal risk); irritation of the skin and respiratory tract upon contact with uncured product.

The results presented above allow a direct and well-argued answer to the question of the impact of polymer systems on the health of the nail plate: the aggregate data support the working hypothesis of a comparatively more sparing profile of hard gels relative to acrylate formulations. The key to this difference is the nature of the damaging action, which can appropriately be decomposed into mechanical and chemical components.

The mechanical component is based on the fact that the high elastic modulus and low allowable deformation of acrylate coatings create persistent stresses in the keratin substrate of the nail. Under cyclic loading (impacts, bending) this leads to the accumulation of microdamage. The situation is exacerbated by procedural steps, namely intensive filing during plate preparation, as well as during correction and removal of the material. Acrylates are specifically associated with conditions such as matrix atrophy and ventral pterygium (overgrowth of the hyponychium), which is consistent with the deeper and more traumatic character of the mechanical impact [3]. Hard gels, possessing greater elasticity and a better capacity to distribute local stresses, reduce the chronic load on the structures of the nail apparatus.

Within the chemical component, the most pronounced differences appear at the stage of coating removal. For acrylates, complete dissolution in acetone remains the standard (soaking for 15–20 minutes). As a strong organic solvent, acetone not only depolymerizes or plasticizes the coating but also extracts lipid fractions from the nail plate and periungual skin, leading to marked dehydration, increased brittleness, and lamellar splitting (onychoschisis). Professional work with hard gels, by contrast, predominantly entails mechanical removal: milling eliminates the bulk of the material while preserving a thin base layer. This strategy minimizes repeated chemical exposure in each service cycle and, consequently, better preserves the integrity of the natural nail [14, 17].

Taken together, the decisive argument in favor of gel systems is the life cycle of the coating: from a more favorable distribution of mechanical stresses to a gentle removal protocol that avoids regular exposure to acetone and the associated degradative changes of the nail plate.

Conclusion

The conducted multifactorial comparative analysis of empirical and theoretical data confirmed the hypothesis and made it possible to formulate a well-grounded conclusion: UV-curable hard gels demonstrate substantial advantages over conventional acrylic compositions by the criteria of biocompatibility and safety profile.

The overall superiority of gel materials has a composite nature. First, at the level of physicochemical processes, photopolymerization proceeds in a controlled mode (according to free-radical curing kinetics with a controllable degree of monomer conversion), which is accompanied by reduced release of volatile organic compounds and residual monomers. This minimizes inhalation and dermal contact exposure risks for the technician and the client. Second, from the standpoint of the biomechanics of the nail unit, the optimal combination of elastic modulus and relaxation coefficient in gel coatings ensures coordinated deformation with the keratin plate. This reduces the concentration of local stresses at the coating–nail interface, lowering the likelihood of microdamage and delamination. Third, the protocol for technological deposition and removal is important: professional work with hard gels assumes gentle mechanical debulking (filing while preserving the base layer), which precludes prolonged exposure to a ketone solvent and, consequently, reduces the risk of chemically induced dehydration and thinning of the natural plate, characteristic of complete dissolution of acrylate systems in acetone.

Therefore, the stated aim — to provide a scientifically rigorous basis for comparing the effects of polymer systems on the health of the nail plate — has been achieved. The totality of the presented evidence indicates that UV-curable hard gels, provided that exposure modes are selected correctly and safety protocols are strictly followed by a qualified professional, are characterized by a measurably lower risk of both mechanical and chemical damage.

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