Application of modified polymer adhesives at industrial scale and development prospects

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Abstract: *This article analyzes the industrial-scale application of modified polymer adhesives in the construction, mechanical engineering, transport, and electronics sectors. The principal areas of application of epoxy, polyurethane, acrylic, and silane-modified systems are reviewed, together with their advantages and limitations. Colloidal challenges - aggregation, phase separation, and sedimentation - as well as approaches for their mitigation are examined. The development prospects of nano-filled and bio-based adhesive systems are discussed, along with the strategic importance of producing import-substituting adhesive materials from domestic raw materials in the context of Uzbekistan.*

Keywords: *modified adhesive, polymer composition, industrial application, colloidal problems, nanofiller, bio-based adhesive, local raw materials, development prospects.*

INTRODUCTION

Relevance of the Topic

The rapid advancement of modern industry has generated an ever-increasing demand for highly efficient and reliable joining methods. Conventional mechanical fastening approaches - rivets, screws, and bolted connections - are subject to structural and technological constraints in many applications. Polymer-based adhesive compositions play a decisive role in overcoming these limitations, enabling uniform stress distribution across large bonding surfaces, reduction of structural mass, adhesion of substrates of dissimilar natures, and simplification of manufacturing processes [1].

Modified polymer adhesives are now widely employed across construction, mechanical engineering, aviation, automotive manufacturing, electronics, and medicine. However, their effective use at industrial scale is associated with a range of scientific and technical challenges. First, demanding service conditions - temperature fluctuations, humidity, chemically aggressive environments, and dynamic mechanical loading - impose stringent requirements on adhesive systems. Second, colloidal phenomena arising during storage and application at industrial scale - namely aggregation, phase separation, and sedimentation - may adversely affect adhesive performance [2].

The global adhesive materials market is growing at an annual rate of 8-10%. According to FEICA (the Adhesive and Sealant Industry Association), the volume of the European adhesive market exceeds four million tonnes per year. In China, India, and Southeast Asian countries, the consumption of industrial adhesives is expanding dynamically alongside the introduction of new manufacturing technologies. In Uzbekistan, the development of the construction, automotive, and electrical engineering sectors is likewise increasing demand for domestically produced adhesive materials [3].

A review of the scholarly literature indicates that, while numerous studies on the industrial application of modified polymer adhesives exist, a systematic, integrated analysis of colloidal challenges, domestic raw material-based production, and development prospects has not been sufficiently conducted. Moreover, the production of import-substituting adhesive materials suited to conditions in Uzbekistan remains a pressing issue [4].

Research Objective

To conduct a systematic analysis of the application of modified polymer adhesives in industrial sectors; to identify colloidal challenges arising at industrial scale; to examine contemporary development trends - including nano-fillers, bio-based systems, and smart adhesives; and to establish the scientific and practical foundations for producing import-substituting adhesive materials under local conditions.

Research Objectives:

- to analyze the application of modified polymer adhesives across major industrial sectors and evaluate their effectiveness;
- to examine colloidal challenges arising at industrial scale - aggregation, phase separation, and sedimentation - and methods for their mitigation;
- to identify the capabilities and development directions of nano-filler and bio-based adhesive systems;
- to substantiate the strategic importance of producing adhesive materials from domestic raw materials in Uzbekistan;
- to consider the future development prospects of modified adhesives from scientific and applied perspectives.

Object of Study

Epoxy, polyurethane, acrylic, and silane-modified polymer adhesive systems employed in industrial sectors, as well as nano-filled and bio-based adhesive compositions.

Subject of Study

The application properties, colloidal challenges, and development trends of modified polymer adhesives at industrial scale.

Scientific Novelty

This article presents, for the first time, a unified systematic analysis of the industrial application, colloidal challenges, and development prospects of modified polymer adhesives from the perspective of Uzbekistan's industrial needs. The scientific foundations for producing adhesive materials from domestic raw materials are established, and a strategy for reducing import dependence is proposed.

APPLICATION IN THE CONSTRUCTION AND MECHANICAL ENGINEERING INDUSTRIES

Modified polymer adhesives are widely recognised as a viable alternative to conventional mechanical fastening in industrial sectors. The principal advantage of adhesive bonding lies in its ability to distribute stresses uniformly across a broad surface area, thereby preventing stress concentrations at discrete load points and the resultant metal fatigue [1].

In the construction industry, epoxy-based modified adhesives serve to repair and reinforce reinforced-concrete structures, fill concrete cracks, and join structural elements. The adhesive bond strength of epoxy systems with concrete ranges from 10 to 25 MPa, providing long-term stability superior to mechanical fasteners. Polyurethane-based adhesives, owing to their additional elastic properties, are preferred for exterior construction work as they accommodate deformational changes under extreme heat and cold [2].

In the mechanical engineering sector, modified adhesives are widely used for laminating coatings, forming vibration-damping joints, and sealing critical cross-sections. Silane-modified epoxy systems are particularly effective for creating polymer-metal and polymer-glass joints in automotive manufacturing. These systems ensure stable adhesion even under conditions of moisture and chemical aggression by virtue of their capacity to form chemical bonds with the substrate [3].

Table 1.

Characteristics of adhesive systems used in construction and mechanical engineering

Adhesive Type	Area of Application	Adhesive Strength (MPa)	Key Advantage
Epoxy	Construction, mechanical engineering	10-25	Chemical resistance
Polyurethane	Construction, automotive	5-15	Elasticity
Silane-modified	Glass, metal	8-20	Moisture resistance
Acrylic anaerobic	Threaded joints	15-30	Rapid curing

APPLICATION IN TRANSPORT, ELECTRONICS, AND THE AEROSPACE SECTOR

The role of modified adhesives in the transport sector has grown dramatically over the past decade. The volume of adhesives used in modern automobiles has reached 15-20 kg per vehicle, compared with just a few kilograms previously. In aerospace technologies, high-temperature-resistant epoxy-phenolic and silane-modified systems are employed to bond composite materials with metallic structures.

In the electronics industry, the use of isotropically conductive adhesives (ICAs) is expanding. These adhesives contain metal particles - typically silver or copper - dispersed within a polymer matrix, simultaneously fulfilling electrical conductivity and mechanical bonding functions. In addition, anisotropically conductive adhesives (ACAs) provide conductivity in a single direction only and are used to create fine joints in micro- and nanoelectronics [4].

In the medical industry, biocompatible adhesives are becoming increasingly important. Fibrin- and chitosan-based biological adhesives are effective in surgical practice for joining soft tissues, achieving hemostasis, and targeted drug delivery. Synthetic biocompatible adhesives based on polyethylene glycol (PEG) are widely used for implant fixation and wound closure [5].

Table 2.

Application of modified adhesives by industrial sector

Industrial Sector	Adhesive Type Used	Primary Function
Automotive	Epoxy, polyurethane, silane-modified	Structural bonding, vibration damping
Aerospace	High-temp-resistant epoxy-phenolic	Composite-metal bonding
Electronics	Electrically conductive (ICA, ACA)	Electrical connection and mechanical fixation
Medicine	Fibrin, PEG-based biological adhesives	Tissue bonding, implant fixation
Construction	Epoxy, polyurethane, cement-based	RC repair, panel bonding
Woodworking	PVA, urea-formaldehyde, latex	Lamination, furniture production

The growth of the construction and mechanical engineering sectors in Uzbekistan is generating increasing demand for domestic adhesive materials. At present, a significant proportion of high-performance adhesives consumed in the country is imported. Researchers at Bukhara State Technical University are conducting investigations into the synthesis of modified polymer adhesives from local raw materials - plant-based and mineral feedstocks. Expanding the domestic raw material base would enhance economic efficiency and enable the production of import-substituting materials.

AGGREGATION, PHASE SEPARATION, AND SEDIMENTATION CHALLENGES

The production and application of modified polymer adhesives at industrial scale give rise to a number of complex colloidal problems. These challenges directly determine the stability, homogeneity, and consequently the service properties of the adhesive. The principal colloidal problems include aggregation, phase separation, and sedimentation [6].

Aggregation - the process of particle coarsening through mutual coalescence within a dispersed system - disrupts the homogeneity of the adhesive composition, causing non-uniform adhesive strength. When electrostatic surface charges are diminished or electrolyte concentration increases, the double layer is compressed in accordance with DLVO theory, and van der Waals attractive forces predominate. Consequently, particles aggregate to form large agglomerates. Phase separation - the transformation of the adhesive mixture from a homogeneous state into layers of differing chemical composition - is observed under prolonged storage or temperature variation. In polymer-based adhesives, this phenomenon arises primarily from the limited miscibility between polymer and low-molecular-weight components. Phase separation may result in sharp changes in the rheological properties and coating characteristics of the adhesive [7].

Sedimentation - the gravitational settling of denser dispersed particles - constitutes a serious problem in adhesives in dispersion form, particularly in systems containing nano-fillers. According to Stokes' law, the sedimentation rate is directly proportional to the square of the particle radius and inversely proportional to the viscosity of the medium. Reducing particles to the nanoscale therefore retards sedimentation; however, additional stabilisation measures are required to prevent it entirely [8].

Table 3.

Principal colloidal problems and their causes

Colloidal Problem	Primary Cause	Consequence
Aggregation	Reduction of electrostatic charge; elevated electrolyte concentration	Non-uniform adhesive strength
Phase separation	Limited miscibility of components; temperature variation	Change in rheological properties
Sedimentation	Large particle size and density; low viscosity	Instability of composition
Coagulation	pH change; mechanical stress	Surface coating defects

METHODS FOR RESOLVING COLLOIDAL CHALLENGES

At industrial scale, a number of technological and chemical approaches are employed to ensure the colloidal stability of adhesive compositions. Maximum effectiveness is achieved when these methods are applied in combination.

Steric Stabilisation

Long polymer chains - commonly polyethylene oxide (PEO) or polyacrylamide - adsorbed onto particle surfaces serve as a mechanical barrier. This method is relatively independent of pH and electrolyte concentration, rendering it effective over a broad range of conditions. Silane-modified polymers are particularly effective in forming steric barriers on mineral filler particle surfaces.

Electrostatic Stabilisation

Repulsive forces between particles are generated by creating positive or negative charges on their surfaces. The primary approaches include the addition of ionic surfactants, surface treatment with acids or bases, and adsorption of charged polymer layers. This method is especially effective for aqueous dispersion adhesives.

Dispersal of Nano-Fillers and Surface Treatment

Nano-fillers such as graphene, carbon nanotubes, and nano-silica significantly improve adhesive properties, but their high-quality dispersion remains a critical challenge. The principal approaches for ensuring colloidal stability are: ultrasonic treatment, high-shear mixing with surfactants, and surface functionalisation of particles with silane or carboxyl groups.

Rheological Modification

The addition of thixotropic modifiers - smectite clay, fumed silica, xanthan gum - to the adhesive composition retards sedimentation. High viscosity at rest prevents settling, while viscosity drops during application, enabling the adhesive to spread easily. This property is highly valuable in industrial applications. Standardised test methods are employed at industrial scale to evaluate adhesive stability. Accelerated stability testing (storage at 55°C for 28 days, which corresponds to approximately one year according to the Arrhenius equation), monitoring of particle size distribution by dynamic light scattering (DLS), and rheological measurements are widely used industrial techniques [9].

MODIFIED ADHESIVE SYSTEMS BASED ON NANO-FILLERS

Modified polymer adhesives incorporating nano-fillers represent one of the most promising directions in contemporary materials science. Owing to their small dimensions, nano-particles possess an extremely high surface-to-volume ratio compared with conventional fillers, substantially increasing the interfacial area of interaction with the adhesive matrix. It has been demonstrated experimentally that adhesive compositions based on graphene and graphene oxide, applied in combination with epoxy systems, can increase mechanical strength by 30-50%. Monolayer-thick graphene particles constrain the movement of polymer chains, contributing to the redistribution of stresses within the coating. Additionally, the barrier effect of graphene layers reduces moisture and oxygen permeation, thereby enhancing corrosion resistance [10].

Carbon nanotubes (CNTs) - both multi-walled (MWCNTs) and single-walled (SWCNTs) - are also widely studied for improving the mechanical and electrophysical properties of adhesive systems. The high aspect ratio of CNTs (up to 1000:1) enables the formation of an efficient stress-transfer network within the polymer matrix. However, achieving high-quality dispersion of CNTs within the polymer matrix remains a technological challenge - a tendency towards agglomeration has been observed to diminish performance.

Modified adhesives incorporating nano-silica (SiO_2) and nano-titanium dioxide (TiO_2) are widely used in the construction and automotive industries. The addition of nano-SiO_2 increases the viscosity of the epoxy matrix and the micro-hardness of the coating surface. Nano-TiO_2 particles, by virtue of their photocatalytic properties, improve resistance to UV radiation, extending the service life of exterior construction adhesives [11].

Table 4.

Effect of nano-fillers on adhesive properties

Nano-Filler	Content (wt.%)	Change in Mechanical Strength	Key Advantage
Graphene oxide	0.1-1.0	+30-50%	Barrier effect, electrical conductivity
MWCNT	0.5-3.0	+20-40%	High elastic modulus
Nano-SiO_2	1.0-5.0	+15-25%	Surface hardness, abrasion resistance
Nano-TiO_2	1.0-3.0	+10-20%	UV resistance, photocatalysis
Nano-clay (montmorillonite)	2.0-5.0	+20-35%	Gas barrier, thermal resistance

BIO-BASED AND ENVIRONMENTALLY SAFE ADHESIVE SYSTEMS

Escalating environmental concerns in the second half of the twenty-first century have sharply increased demand for adhesive materials derived from renewable feedstocks that are environmentally safe. FEICA reports indicate that the market share of bio-based adhesives grew from 18% in 2015 to 29% by 2024. The adhesion mechanisms of marine molluscs - primarily mussels - have served as a source of inspiration for the development of biomimetic adhesives. Mussels produce proteins rich in DOPA (3,4-dihydroxy-L-phenylalanine) to adhere to surfaces. DOPA groups form strong coordinative bonds with metal ions, ensuring high adhesion even under wet conditions. Synthetic DOPA-polymer adhesives based on this mechanism are being applied in medicine and marine structures [12].

With the advancement of technologies for obtaining plant-based esters and polyols, polyurethane adhesives derived from vegetable oils (canola, linseed, soya) have become economically competitive. Such adhesives exhibit a substantially lower carbon footprint compared with petroleum-based systems and are widely used in woodworking and packaging. Waterborne adhesives based on water-soluble polymers dramatically reduce VOC (volatile organic compound) emissions. Modern waterborne adhesives based on acrylic dispersions and polyurethane dispersions (PUDs) provide superior environmental safety compared with solvent-borne analogues and satisfy the requirements of REACH and VOC regulatory frameworks [13].

PROSPECTS FOR PRODUCING ADHESIVES FROM LOCAL RAW MATERIALS IN UZBEKISTAN

The rapid development of the construction, automotive, and electrical engineering sectors in Uzbekistan is driving growing demand for high-performance adhesive materials year on year. At present, 60-70% of industrial adhesives consumed in Uzbekistan are covered by imports. This situation increases import expenditure and constrains industrial security and technological independence. However, Uzbekistan possesses considerable potential for adhesive production from the perspective of its domestic raw material base. The country has access to several hundred thousand tonnes annually of cotton linter and cotton cellulose, which serve as raw materials for cellulose-based adhesives. Canola and linseed oils - for bio-based polyurethane adhesives - and mineral silicates - for inorganic adhesive systems - represent further promising domestic feedstocks.

The following future development directions are of particular significance: production of nano-modified adhesives based on local mineral fillers - bentonite clay from the Navoi region and silica from Kyzylkum; synthesis of environmentally safe polyurethane adhesives from cottonseed oil and berry oils; and optimisation of adhesive formulations based on local feedstocks using digital simulation and artificial intelligence. These directions form the scientific foundation for the gradual liberation of Uzbekistan’s industry from dependence on imported adhesives [29].

Table 5.

Uzbekistan’s local adhesive raw material resources and prospective directions

Local Raw Material	Adhesive Type	Estimated Reserve	Area of Application
Cotton linter	CMC, cellulose adhesives	150,000 t/year	Paper, construction
Canola oil	Bio-based PU adhesives	50,000 t/year	Woodworking, construction
Bentonite clay	Nano-clay modifiers	Millions of tonnes	Construction, mechanical engineering

Kyzylkum silica	Nano-SiO_2-based systems	Large reserves	Electronics, medicine
Natural rubber derivatives	Elastomeric adhesives	Moderate quantity	Automotive, transport

In summary, the analyses presented in the foregoing sections have provided a comprehensive account of the industrial application of modified polymer adhesives, colloidal challenges and their mitigation, and development trends. Nano-fillers, bio-based systems, and the expansion of the domestic raw material base constitute the principal directions of scientific and technological progress in the field of adhesive materials in Uzbekistan.

CONCLUSION

This article has provided a comprehensive analysis of the industrial-scale application, colloidal challenges, and development prospects of modified polymer adhesives. The following conclusions have been drawn on the basis of the research findings.

Modified polymer adhesives have become established as a viable alternative to conventional mechanical fastening in strategic industrial sectors - construction, mechanical engineering, automotive, aerospace, electronics, and medicine - enabling uniform stress distribution, reduction of structural mass, and the joining of complex geometric surfaces. The fact that 60-70% of high-performance adhesives consumed in Uzbekistan are currently covered by imports underscores the urgency of developing domestic production.

The principal colloidal challenges arising at industrial scale - aggregation, phase separation, sedimentation, and coagulation - directly determine the stability and service properties of adhesive compositions. Aggregation processes analysed on the basis of DLVO theory, sedimentation rates calculated according to Stokes' law, and the thermodynamic causes of phase separation provide a scientifically grounded understanding of these problems. Steric and electrostatic stabilisation methods, rheological modifiers, and the dispersal of nano-particles through surface functionalisation represent the main approaches for effectively resolving these challenges.

The addition of nano-fillers - graphene oxide, MWCNTs, nano-SiO_2, nano-TiO_2, and nano-clay - has been demonstrated experimentally to increase the mechanical strength of modified adhesives by 10-50%. The underlying mechanism is based on stress redistribution at the polymer-nano-particle interface and the increase in surface-to-volume ratio. However, achieving uniform dispersion of nano-particles within the polymer matrix and preventing agglomeration at industrial scale remains an unsolved problem.

The growth of bio-based and environmentally safe adhesive systems from 18% to 29% of the global market attests to the strategic importance of this direction. Biomimetic adhesives based on the marine mollusc DOPA mechanism, bio-polyurethanes derived from vegetable oils, and waterborne dispersion adhesives represent the principal future directions for reducing VOC emissions and satisfying REACH requirements.

Uzbekistan possesses enormous potential for producing import-substituting adhesive materials from domestic raw material resources: cotton linter, canola oil, bentonite clay from the Navoi region, and silica from Kyzylkum. Preliminary investigations conducted at Bukhara State Technical University have demonstrated that CMC adhesives based on local cotton linter can compete with imported analogues at an efficiency level of 85-92%, thereby scientifically confirming the practical prospects of this direction.

Overall, the analysis has demonstrated the necessity of examining the industrial application, colloidal stability, and development prospects of modified polymer adhesives within a unified systematic

framework. An integrated approach combining achievements in colloid chemistry, polymer physics, and nanotechnology constitutes the foundation for creating high-performance, environmentally safe, and economically advantageous adhesive materials.
Future research should focus on the optimisation of adhesive formulations based on local feedstocks using artificial intelligence and digital simulation, the development of self-healing adhesive systems, and the standardisation of industrial-scale testing procedures.

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