

## ENHANCED BIOCOMPATIBILITY AND TENSILE STRENGTH OF POLYURETHANE/NANOSILICA NANOCOMPOSITES FOR ORTHOPEDIC IMPLANTS

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### Abstract

This study is about the use of nanosilica gel with biopolymers such as polyurethane, which has extraordinarily little elastic and toxic effect on human blood, and which works in fields and medical applications that deal with the activities of the human body. It is better to improve the contrast of silica with biopolymers, mechanical, and biological properties. The results show that the use of nanomaterials in small proportions of 1%, 3%, and 5% by volume makes the toxic property almost non-existent. The mechanical properties, tensile strength, impact resistance, and hardness showed acceptable values under the effect of human body fluids (blood, saliva, seminal, urine, stomach fluid), which failed extremely hard with stomach fluids compared to the base material for the reinforced materials and their ratios. Increasing nanosilica gel concentration generally improves tensile strength between 20 and 50 MPa under all conditions. Increasing nanosilica gel concentration generally improves tensile strength between 20 and 50 MPa under all conditions. The highest tensile strength, of ~50 MPa, is recorded for the dry samples with 5% nanosilica, while the lowest, of around ~10 MPa at 0% nanosilica, appears in the acidic medium, with pH 1.5-3.5. Increasing the nanosilica content enhances hardness under all conditions, within 40-90 on the Rockwell hardness scale. The desired application is to improve resistance, reduce biodegradation, and reduce the percentage of toxicity, and this is what resulted in the study of chemical properties as well.

Keywords: Biopolymer, Nano silica gel, Composites, Impact resistance, Hardness, Biodegradation, Human body fluid, pH measurement.

## 1. Introduction

Biopolymers are widely used in many fields, including medicine and biomedical engineering, particularly with the use of differentiated silica with biopolymers. These materials combine the properties of biopolymers, including decomposition under various conditions, with the mechanical benefits provided by the presence of a reinforcing material such as differentiated silica [1].

Wang and Wang [2] have selected polyurethane as a biopolymer material for the preparation of medical implants. They also explain the use of polyurethane in biomedical applications, including light-consistency evaluation, disinfection-resistant heart implants, and medical supplies. They explain here, with a future view of polyurethane, that the development in this field has increased the expansion of such industries. Ward and Jones [3] reported that the medical and agricultural device industry is a synthetic material.

Initially, however, designers used commercial polymers that were developed for a variety of industrial applications. The development of a hybrid polyurethane with silica, Avcothane™-51, was used in intra-aortic balloons in the 1960s and was the first polymer developed as a "serious material". Here, the inventor of the wine cabinet changed the handbag to fit the biological needs of the human body. This has been the subject of numerous research and patents.

Polyurethane is a high-performance material, specially designed for general and specific medical applications. Fathi-Karkan et al. [4] stated that polyurethane is a biomaterial used in therapeutic medicine as an alternative to blood vessels. However, one drawback is the potential for eventual thrombosis, which reduces its functional potential. The continued use of these biopolymers in vascular tissue engineering, combined with the physical and chemical benefits of these materials, highlights the potential of polyurethane, providing a broad target for future research.

Li et al. [5] proved that effective polyurethane composites were prepared, and their mechanical properties, molecular applications, electronic damage analysis, optical analysis, and Fourier transform infrared spectroscopy (FTIR) techniques were studied, respectively. The work diagnostics during the application. Surface morphology was measured using a microscope (SEM). Fourier transform infrared (FTIR) spectroscopy showed that the polyurethane was reflectively incorporated with the hydroxyl oil.

The silicone-based polyurethane composite, containing 8% hydroxyl oil, was found to have the best combination and usability in a suitable damping environment. Yang et al. [6] studied a special type of coating using organic silicone with polyurethane. Such applications have been carried out in medical facilities in many countries. It is a water-repellent and acid-repellent coating for lengthy periods of time, which makes its use ideal for operating rooms.

Continuous progress in research, as biopolymers contribute to drug delivery, as the body is fundamentally involved in different biomedical devices. They also serve as part of the human body, such as the kidney membranes. Intra-aortic balloons, heart valves, temporary scaffolds, and breast implants all have medical applications, allowing for customization of their physical and chemical properties, leading to success in applications, particularly in the medical and pharmaceutical fields. Polyurethane's physical and mechanical stability and potential for application in drug delivery [7]. Polyurethanes have highly variable properties, offering a wide variety

of applications. They are used in biomedical fields, including insulated wires for pacemakers, implants, heart valves, and prosthetics [8].

In their study, Zhou et al. [9] developed models made of polyurethane with reinforced aluminium oxide and titanium. The purpose of the reinforcement is to strengthen the composites in terms of tensile strength and elongation in the case of various medical uses. The toxicity of the composites was also studied when used inside the body, as the human body reacts in small quantities with oxides. Furthermore, Wendels and Av'erous [10] emphasize that biopolymers, particularly polyurethanes, have been identified for their long-term medical suitability, and within this context, for the design of novel adaptive medical devices. New polyurethanes, with their memory and smart properties for adaptable shape formation, are beginning to emerge, bridging the gap between bio- and non-biological materials. This is of immense importance for students' understanding of the uses of polyurethanes.

Chattopadhyay and Raju [11] aimed to develop high-performance polyurethane coatings. It also examines the use and properties of polyurethane and the production of high-performance polyurethane films. It also focuses on reviewing polyurethane chemistry and the importance of its by-products, such as biuret. Ghosh et al. [12] used polyurethane in the manufacturing of biomedical devices, including blood oxygenators, catheters, heart valves, dialysis, stents, vascular prostheses, surgical dressings, biodegradable structures, and drug delivery systems, due to its high content for excellent diagnostic compatibility.

Wang et al. [13] Contributing to the use of nanomaterials, such as deficient performance and lack of long-term patentability, are the potential benefits of using nanomaterials. Nanomaterials can improve the compatibility, antibacterial effect, mechanical strength, and biodegradability of medical polyurethanes. Nanomaterials are used in a variety of sectors, including modified nanocomposites. Cui et al. [14] noted that, in spite of the wide use of polyurethane in biomedical applications, with the primary purpose in drug delivery, their mechanical properties, integrity, and flexibility are limited. Its.

Mills et al. [15] aimed to investigate the use of nano-silica on the various properties of polyurethane coatings, which exhibit high mechanical and toxic properties, and their impact on the composites added to them and the amount of additives. Natural biopolymers, such as collagen, chitosan, and gelatine, can be reinforced with nanomaterials to improve their mechanical and biological properties [16]. Synthetic biopolymers, such as polylactic acid (PLA), polyglycolic acid (PGA), polycaprolactone (PCL), and polyurethane, can be modified with nanomaterials to improve their biocompatibility and interaction with tissues [17].

However, it is noted that there is a need to develop an effective methodology for incorporating nano-silica gel into the polyurethane matrix with homogeneous dispersion and tailored surface modification, achieving improved mechanical and chemical properties while preserving processability. This research aims to develop bio-polyurethane composites reinforced with nano-silica gel by improving the dispersion of nanoparticles within the polymer matrix and chemically modifying their surfaces to enhance interfacial compatibility, with the goal of improving the material's mechanical and chemical properties while maintaining its processability for industrial applications.

This work contributes to the nanocomposite of polyurethane/nanosilica gel for medical applications in contact with the human body. The research introduces a tailored surface-modified nano-silica gel into polyurethane composites through a controlled synthesis–dispersion approach, enabling simultaneous enhancement of mechanical and chemical properties without compromising industrial processability. The shape of a projectile is generally selected on the basis of combined aerodynamic, guidance, and structural considerations. The choice of seeker, at supersonic speeds, and careful selection of the nose and tail shapes are mandatory to ensure performance and operation of the overall nano-silica gel with volume fractions of 1%, 3%, and 5%.

## 2. Materials and Methods

This work consists of the preparation and characterization of newly developed biomedical nanocomposite materials composed of polyurethane/nanosilica gel. The methodology is summarized in the flowchart shown in Fig. 1.

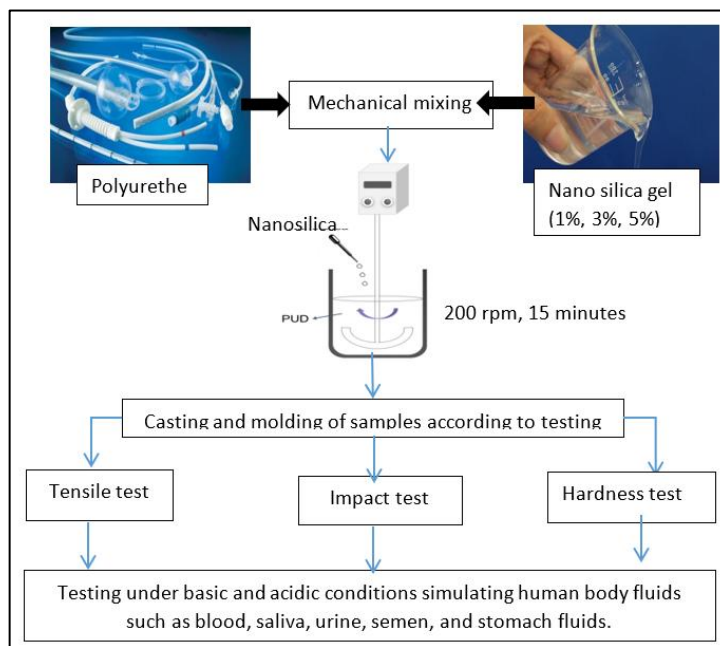


Fig. 1. The experimental procedure.

### 2.1. Materials

Medical-grade polyurethane was selected as the primary polymer matrix due to its biocompatibility and flexibility. Silica gel nanoparticles ( $\text{SiO}_2$ ) with an average particle size of 50 nm were used as the reinforcing filler. All solvents and chemical agents utilized were analytical grade.

#### 2.1.1. Polyurethane

Polyurethane is a versatile polymer that has been widely used in medical devices due to its excellent mechanical properties, biocompatibility, and biodegradability.

However, the incorporation of silica nanoparticles into polyurethane matrices has been shown to enhance the material's properties, making it more suitable for use in medical applications [18]. The general chemical formula for polyurethane is  $[-NH-CO-O-R-O-CO-NH-R']_n$  where:  $-NH-CO-O-$  is the urethane group. R and R' are different chemical chains that can be aliphatic or aromatic [19].

Polyurethane is composed of urethane units connected by urethane bonds. The structure of polyurethane, as shown in Fig. 2, is  $[-NH-CO-O-R-O-CO-NH-R']_n$ , where n is the number of repeating units in the polymer chain [20]. Polyurethane may consist of urethane units with their own letters via urethane bonds with ether bonds. The unique chains and units can be repeated, forming polyurethanes. Modern nanosilica-reinforced polyurethane polymers are making significant progress in medical applications, according to numerous studies and research. Their dimensions are heavy compared to the amount of polyurethane used in these applications [21].

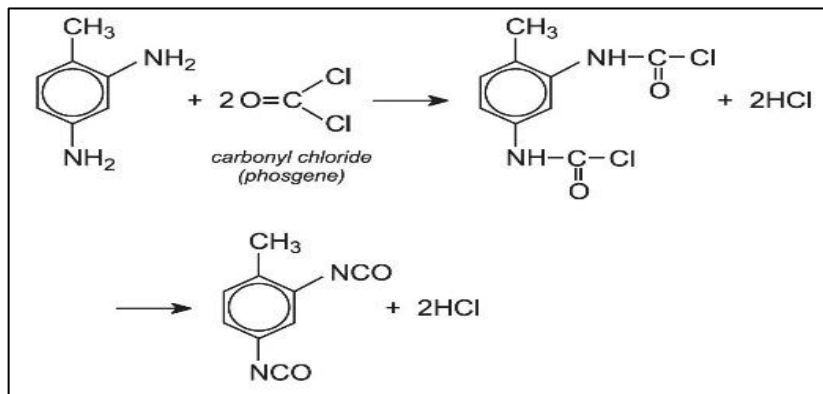


Fig. 2. Chemical structure of polyurethane [21].

### 2.1.2. Nanosilica gel

Nanosilica gel is one of the most important and widely used materials in medical devices, drug delivery systems, wound healing, and medical imaging. The chemical formula and structure are shown in Fig. 3. Thanks to its high affinity for human skin, nano silica gel's unique applications include its safe compatibility with the body, providing a variety of easy-to-use materials for applications that could potentially put human life at risk [22].

The most important medical applications for which nanosilica gel is used are the manufacture of prosthetic limbs and medical implants. It is also used in imaging to transmit images of the internal body using ultrasound waves. It is also used to deliver drugs in a way that is compatible with the body. All of these applications are attributed to the properties of nanosilica gel (Table 1), including its mechanical capabilities, biocompatibility, and ability to be absorbed by the body's tissues [23].

Table 1. The physical properties of nano silica gel [24].

Diameter (nm)	Density (g/cm <sup>3</sup> )	Surface volume ratio (m <sup>2</sup> /g)	Melting point (°C)
20-30	2.1	130-600	1600

Nanosilica gel is a mixture of nanosized silica particles dispersed in a liquid, usually a gel or semi-solid. These nanoparticles are used in various applications, including medicine. Their chemical composition is silicon oxide, which is found in sand and quartz, but the particle size is exceedingly small, reaching 10-30 nanometres [25].

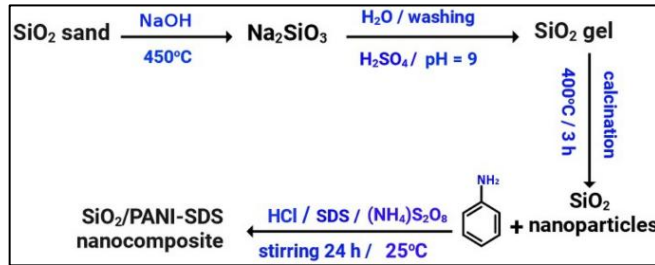


Fig. 3. Chemical formula and structure of nanosilica gel [26].

There is a condition under which all patients would be examined. The acidity and alkalinity levels of human body fluids vary depending on the diet followed or the medical history that exposes the body to the use of medications that may alter the acidity level in the human body, including Blood, which has a basic value ranging from 7.35 to 7.45; Saliva was relatively neutral to alkaline, 6.2 to 7.6; Semen, which is considered very basic, between 7.2 and 8; Urine, 4.5 to 8; and Gastric fluid, 1.4 to 3.5 [27].

### 2.1.3. Preparation of silica gel nanoparticles

Silica nanoparticles were prepared using the sol-gel method. Tetraethyl orthosilicate (TEOS) was hydrolysed in an acidic aqueous medium under continuous stirring. The resulting gel was aged, washed with distilled water, and dried at  $120\text{-}180^\circ\text{C}$  to obtain silica nanoparticles. Particle size distribution was confirmed using dynamic light scattering (DLS).

### 2.1.4. Fabrication of polyurethane/silica nanocomposites

Nanocomposites were prepared by dispersing silica nanoparticles into the polyurethane matrix at different volume fractions of 0%, 1%, 3%, and 5%. Nanoparticles were ultrasonically dispersed in the polyurethane prepolymer for 60 minutes to ensure uniform distribution. The mixture was cast into moulds and cured at controlled temperature conditions to obtain solid composite sheets. It was then moulded after homogeneous mixing and purred with suitable shapes according to ASTM of testing under simulated human body fluid conditions with different pH values.

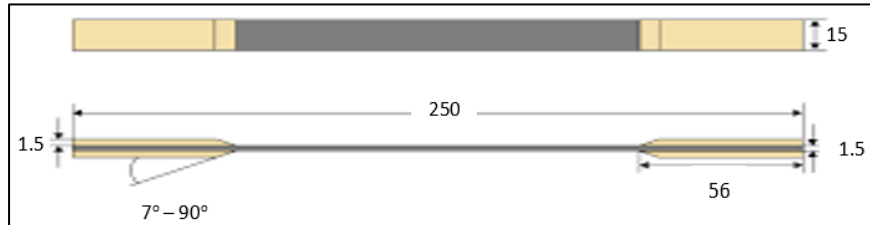
## 2.2. Experimental method

### 2.2.1. Testing methods of mechanical properties

The most important mechanical properties studied in this paper are the tensile strength, impact resistance, and hardness. All of them were tested in two stages without exposure to body fluids. The second stage involved immersing the models in fluids with acidic and basic levels similar to those in human body fluids for a period of 30 days. Mechanical properties were evaluated according to ASTM standards.

### i. Tensile test

Tensile strength is a dependence of the mechanical properties of materials, where polyurethane is particularly exposed to a special force until it reaches the point of collapse. The idea of using silica diffusers makes the mechanical gain of polyurethane greater than it is alone, even after exposure to acidic and basic levels, where the mechanical properties were studied in terms of biodegradation [28]. Tensile strength and elongation at break were measured using a universal testing machine, as shown in Fig. 4.



**Fig. 4. Tensile sample of polyurethane reinforced with nano silica gel according to ASTM D3039 [28].**

ASTM D3039 characterization standard is used to measure the tensile strength,  $\sigma$ , of composites reinforced with nanomaterials. The maximum tensile force,  $F_{max}$ , is applied until the specimen breaks, and the tensile strength is calculated using the formula of Eq. (1) [28].

$$\sigma = \frac{F_{max}}{A} \quad (1)$$

where A is the partial width area ( $m^2$ ).

### ii. Impact resistance

The ability of a material to withstand and absorb energy resulting from sudden stress without breaking or being damaged. Izod impact strength measurement has been adopted for polyurethane compounds with nanosilica gel according to ASTM D256 [29, 30], using a universal testing machine, as shown in Fig. 5.



**Fig. 5. Izod impact testing of polyurethane reinforced with nanosilica gel.**

To calculate the capacity of polyurethane composites reinforced with a gel containing silica nanoparticles, a special equation is used. Nanocomposites based on the size and shape of the nanoparticles and their mechanical properties [31].

$$G_c = G_m \times (1 + V_f(G_f/G_m - 1)) \quad (2)$$

where  $G_c$ : Impact resistance of the composite (J),  $G_m$ : Impact resistance of the matrix material (J),  $G_f$ : Impact resistance of the reinforcing material (J), and  $V_f$ : Volume fraction of the reinforcing material (%).

### iii. Hardness testing

ASTM D4672 standard was used to measure the hardness of plastic materials and composites using the Rockwell Hardness test [32]. The type of polyurethane used could affect the test results. Also, the size and shape of nanosilica particles can affect their distribution and interaction with polyurethane, leading to improved mechanical properties. Another factor that might affect the mechanical properties of the composite is the nanosilica addition ratio.

Hardness was assessed using the Shore A or D scale, depending on the material's hardness level, as shown in Fig. 6 [33].

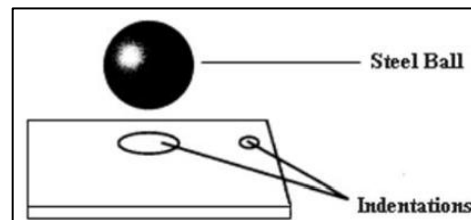


Fig. 6. Rockwell Hardness test of polyurethane reinforced with nanosilica gel [33].

### 2.2.2. Chemical properties

The chemical properties of polyurethane/silica nanocomposites have also been studied. The incorporation of silica nanoparticles has been shown to improve the material's resistance to degradation. This is due to the silica nanoparticles' ability to form a protective layer on the surface of the material, which can prevent water and other chemicals from penetrating the material [34]. ASTM D6954-18 standard guide for exposing and testing plastics that degrade in the environment by a combination of oxidation and biodegradation was used as recommended by Patwary and Mittal [35].

Nanocomposites with different concentrations of nanofiller were prepared by adding nanosilica filler to the single-phase polyurethane matrix. A control series was prepared with the same concentrations of micron-sized silica. The nanosilica filler was amorphous, giving composites with the polyurethane that were transparent at all concentrations [36].

### 2.2.3. Swelling and degradation in simulated body fluids

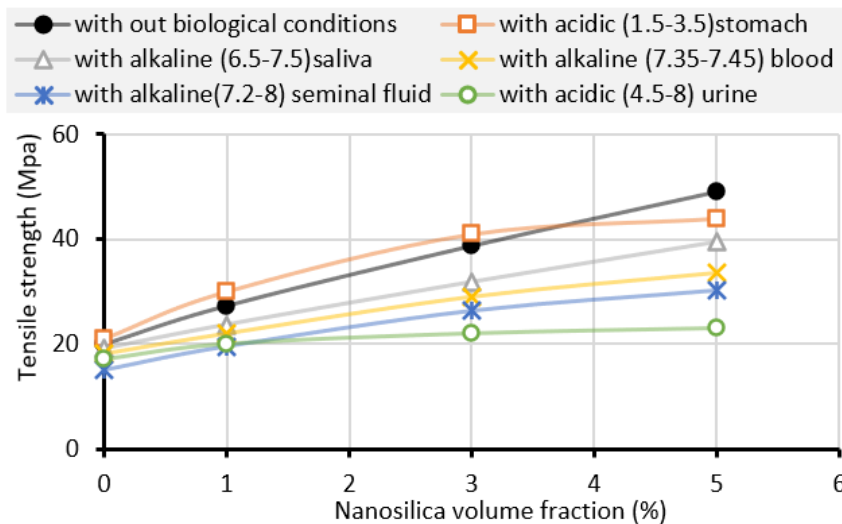
To assess biostability and suitability for medical applications, samples were immersed in simulated body fluid (SBF) or phosphate-buffered saline (PBS) at 37

°C for up to 30 days. Weight change due to swelling was measured at regular intervals. The degradation rate was evaluated by mass loss.

### 3. Results and Discussion

#### 3.1. Tensile strength

Figure 7 shows the effect of human body fluids on tensile strength values of polyurethane nanocomposites reinforced with nanosilica gel. The figure illustrates the effect of different biological conditions on the tensile strength of a material as a function of SiO<sub>2</sub> gel volume fraction.



**Fig. 7. Tensile strength results with nanosilica gel volume fraction under the effect of the human body fluids.**

The x-axis represents the concentration of SiO<sub>2</sub> gel (ranging from 0 to 5%), while the y-axis shows the tensile strength measured in MPa (from 0 to 60 MPa). Multiple conditions are compared with the pure sample, which shows the highest tensile strength among all conditions, and this is consistent with the references [37]. Strength increases significantly with higher SiO<sub>2</sub> content, reaching nearly 50 MPa at 5% SiO<sub>2</sub>. Indicates that the material performs optimally in the absence of any biological fluids, and this is consistent with the references[38]. With an acidic stomach of pH 1.5–3.5, results exhibit the lowest tensile strength, starting around 10 MPa at 0% SiO<sub>2</sub>. Similar observations have been reported by Caseri [39].

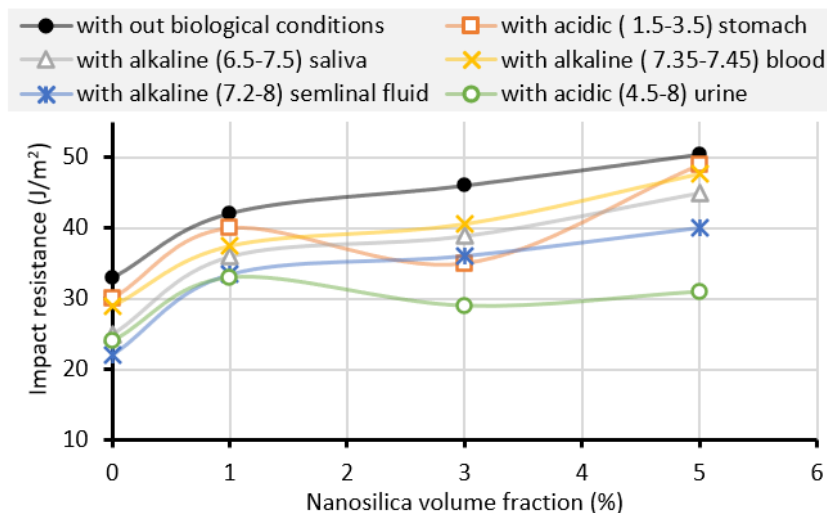
Slight increase with SiO<sub>2</sub> content, but remains well below other conditions, ending just under 20 MPa. Suggests that highly acidic environments significantly weaken the material, and this is consistent with the references[40]. With alkaline saliva, pH 6.5–7.5, the results show moderate tensile strength, starting around 18 MPa at 0% SiO<sub>2</sub> and reaching about 40 MPa at 0.05% SiO<sub>2</sub>. Indicates a better performance than acidic conditions but slightly lower than non-biological conditions. With alkaline seminal fluid (pH 7.2-8) [41], tensile strength starts around 17 MPa and increases gradually to about 28 MPa. Demonstrates that

seminal fluid mildly affects the tensile strength, reducing it compared to non-biological conditions, which agrees with the findings of Elsayy et al. [42].

With alkaline blood with a pH of 7.35-7.45, there is a steady increase from roughly 17 MPa to 32 MPa. It indicates that blood slightly reduces tensile strength compared to non-biological conditions, but performs better than saliva or seminal fluid, and this is consistent with the references [43]. With acidic urine (pH 4.5-8), tensile strength starts near 17 MPa and rises gradually to about 22 MPa at 5% SiO<sub>2</sub>. Suggests that acidic urine mildly affects tensile strength, similar to seminal fluid, but less than acidic stomach conditions, and this is consistent with the references [43, 44].

### 3.2. Impact resistance

The impact resistance of composites reinforced with a gel containing silica nanoparticles during a period of 30 days under the influence of liquids will show the changes obtained through Fig. 8. The figure illustrates the effect of pH values of various human body fluids on the impact resistance (J/m<sup>2</sup>) of polyurethane composites reinforced with nano-silica gel (SiO<sub>2</sub>). Interpretations of the effect of human body fluids on impact resistance effect of fluids on polymer structure, show that fluids could interact with the polymer, leading to changes in the material's structure and mechanical properties. This can affect the impact resistance of the nanocomposites. A similar conclusion has been drawn by Vitacolonna et al. [45]. The presence of silica particles enhances the ductility of polyurethane and strengthens it even in the event of exposure to biodegradation.



**Fig. 8. Tensile strength results with nanosilica gel volume fraction under the effect of the human body fluid.**

Figure 8 demonstrates that the addition of SiO<sub>2</sub> significantly enhances the tensile strength of the polymer composite under all tested conditions. The highest value (~50 MPa at 5% SiO<sub>2</sub>) is recorded for the dry samples, while the lowest (~10 MPa at 0% SiO<sub>2</sub>) appears in the acidic medium, pH of 1.5-3.5. These results indicate that both the SiO<sub>2</sub> content and the surrounding medium strongly affect the mechanical performance of the material [46]. Samples exhibited the highest impact

resistance, reaching approximately  $J/m^2$  at 5%  $SiO_2$ , with a steady increase as the silica content rose. This indicates that the material maintains excellent mechanical performance in dry environments, where the polymeric network remains chemically stable and unaffected by degradation.

The improvement in impact resistance with increasing  $SiO_2$  content can be attributed to the filler reinforcement effect. Silica particles act as rigid inclusions that transfer the applied load from the polymer matrix to the filler, provided that dispersion and interfacial adhesion are adequate. At low filler concentrations, the improvement is gradual, but as the  $SiO_2$  content approaches a percolation threshold, the formation of a continuous reinforcing network enhances load transfer efficiency, resulting in a sharp increase in strength [47].

Interfacial adhesion and environmental effects are effective factors on the quality of the polymer–silica interface. Strong interfacial bonding through hydrogen bonding or silane coupling improves stress transfer and delays crack propagation. However, exposure to acidic environments leads to hydrolysis or partial dissolution of the silica surface, weakening the interfacial bonding and promoting debonding at the filler–matrix interface, and this is consistent with the references [48].

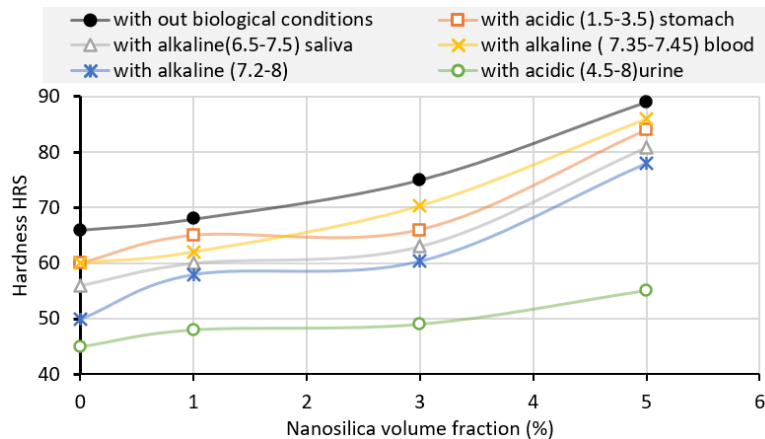
The samples showed relatively high and close impact resistance values between 35 - 45  $J/m^2$  at the highest  $SiO_2$  concentration. This suggests that mildly basic conditions have no significant adverse effect on mechanical performance due to limited hydrolytic degradation. Additionally, immersion in liquids can induce swelling and plasticization, which reduce the stiffness and cohesive strength of the polymer network [49]. In the dry state, fracture likely occurs cohesively within the matrix, where silica particles effectively resist deformation and enhance fracture resistance.

In contrast, under acidic or wet conditions, the failure tends to be interfacial, initiated at debonded regions or voids around filler particles, resulting in significantly lower tensile strength, which was also noticed and reported by Zini et al. [50]. Samples exhibited the lowest impact resistance, especially in simulated gastric conditions, where resistance decreased to around 15  $J/m^2$  at 5%  $SiO_2$ . This demonstrates that acidic conditions weaken the polymer structure and reduce the reinforcement efficiency of silica nanoparticles.

### 3.3. Hardness analysis

Figure 9 illustrates how the pH values of various human body fluids influence the hardness (HRS) of polyurethane nanocomposites reinforced with nano-silica gel. Without biological conditions, the samples exhibited the highest hardness, increasing from about 65 HRS at 0%  $SiO_2$  to nearly 88 HRS at 0.05%  $SiO_2$ , and this is consistent with [51] results. This indicates that the incorporation of nano-silica effectively enhances hardness in dry environments due to strong physical interactions and hydrogen bonding between silica and the polyurethane matrix. While in alkaline biological media, saliva with a pH of 6.5-7.5, blood with a pH of 7.35-7.45, and seminal fluid with a pH of 7.2-8, showed relatively high hardness values ranging from about 60-80 HRS at the highest  $SiO_2$  concentration, which agrees with the results of Jaganathan et al. [52].

These results suggest that alkaline and near-neutral conditions do not significantly degrade the polymer structure, allowing the composite to retain its mechanical strength. In acidic environments, the stomach with a pH of 1.5-3.5, urine with a pH of 4.5-8, the hardness dropped considerably, especially in the simulated gastric environment, where values did not exceed 40-45 HRS even at 5% SiO<sub>2</sub>. This sharp decrease confirms that acidic conditions lead to chemical degradation of the polyurethane matrix and weaken the interfacial bonding with silica nanoparticles, and this is consistent with the references [53].



**Fig. 9. Hardness results with nanosilica gel volume fraction under the effect of the human body fluid.**

#### 4. Conclusion

This work included the development of a biomedical nanocomposite material for various medical applications. The developed nanocomposite includes polyurethane strengthened by nanosilica gel and then characterized for its mechanical and chemical properties. The results show that increasing SiO<sub>2</sub> gel concentration improves tensile strength by 20 and 50 MPa under all conditions. Highly acidic conditions (stomach) have the most detrimental effect, while neutral or slightly alkaline biological fluids have moderate effects. Increasing SiO<sub>2</sub> content enhances hardness under all conditions by 40-90 HRS, but acidic media significantly reduce it due to polymer hydrolysis and weakened interfacial bonding.

These findings highlight the need to improve chemical and interfacial stability for reliable performance in variable physiological environments. The best performance of mechanical and chemical properties is observed in the pure samples, emphasizing the impact of biological environments on material integrity. The pH level of human body fluids has 15-52 J/m<sup>2</sup> impact resistance of polyurethane composites reinforced with nano-silica gel. Acidic environments induce polymer chain degradation and weaken interfacial bonding, leading to a notable reduction in mechanical properties.

The study of using nanosilica with biopolymers for human body applications is a promising area of research. The expected outcomes of this study can contribute to the development of new bio-polymer nanocomposites with improved mechanical and biological properties, making them suitable for medical applications.

**Nomenclatures**

$A$	Area (mm <sup>2</sup> )
$F$	Applied force (Newton )
$G_c$	Impact resistance of the composite (Joules)
$G_m$	Impact resistance of the matrix material (Joules)
$G_f$	Impact resistance of the reinforcing material (Joules)
$V_f$	Volume fraction of the reinforcing material. (%)

**Greek Symbols**

$\sigma$	tensile strength (MPa)
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**Abbreviations**

FTIR	Fourier transform infrared spectroscopy.
PCL	polycaprolactone
PGA	polyglycolic
PH	potent hydrogen
PLA	polylactic
SEM	scanning electron microscopy
SiO <sub>2</sub>	Silicon dioxide
TPU	Thermoplastic polyurethane

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