



REVIEW PAPER

Recent Advances in Magnetic Slime Robots: Materials, Self-Healing, Reconfigurability, and Multifunctional Applications

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Article Information

Received: 08 July 2026
Revised: 28 August 2026
Accepted: 06 September 2026
Available online: 09 September 2026

Keywords:

Non-Newtonian
Elastomer
Self-Healing
Polyvinyl Alcohol (PVA)
Magnetic particles

Abstract

A Magnetic Slime Robot is a non-Newtonian fluid-based magnetically actuated soft robot that is flexible and reconfigurable in nature. These robots are composed of Magnetized particles and a polymer-based gel-like substance, allowing them to move freely in multiple directions and pass through narrow spaces. However, slime robots exhibit better deformability than elastomer-based soft robots. These elastomer-based soft robots are also not capable of being reconfigured and passing through narrow spaces due to their predesigned shapes and sizes, which makes slime robots unique from elastomer-based robots as well as conventional rigid robots. However, the preparation technique for Magnetic slime robots is also unique and different, where the magnetic particles (NdFeB or nano-ferromagnetic) and borax were added to a PVA (polyvinyl alcohol) solution to prepare them, with the addition of magnetic particles (NdFeB or nano-ferromagnetic), which makes slime toxic and non-biocompatible in nature. To avoid the toxicity of magnetic slime, these particles were coated with SiO₂ particles via the Stober method. Experimental results show that magnetic slime robots can elongate more than seven times their original length under a strong permanent magnet (NdFeB) and deform into complex shapes such as circles, hexagons, and rings under a configured magnetic field. Owing to their self-healing and reconfigurability, slime robots are used in applications such as microscale navigation, targeted drug delivery, electronic circuit repair, and foreign object retrieval.

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1. Introduction

A slime robot is a soft, flexible, and self-healing robot made by mixing magnetic particles with a polymer-based gel. This combination allows the robot to move freely in different directions. [1]. These robots come under the categories of soft robotics and offer superior properties and capabilities compared to traditional robots [1,2]. A slime robot is a kind of non-Newtonian fluid-based magnetically actuated soft robot, which exhibits better deformability than elastomer-based soft robots. Their unique structure enables them to adapt their shape according to the surrounding environment and external magnetic field. The combination of flexibility, mobility, and self-healing ability makes these robots suitable for various

biomedical and engineering applications where conventional rigid systems may face difficulties during operation. These elastomer-based soft robots possess limited deformation capabilities compared to fluid-based soft robots (slime robots) due to their predesigned shapes and sizes. Moreover, elastomer-based robots are not capable of being reconfigured and passing through narrow spaces as compared to Magnetic slime robots [1, 3]. Basically, Magnetic slime robots combine the properties of non-Newtonian fluids and elastomers, which offer a promising solution for targeted drug delivery and are helpful for carrying out tasks like transporting, ingesting and gripping solid items with safety, accuracy, and with quick response [1-3]. This research paper also discusses the design, preparation, and application of magnetic slime robots in detail.

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<https://doi.org/10.36037/IJREI.2026.10507>

2. Materials and their properties

2.1 Materials Needed

This Research article also discussed about material needed for the preparation of magnetic slime robots. Basically, four major types of materials are used to prepare magnetic slime robots: polyvinyl alcohol (PVA), Borax solution, Magnetic particles, and magnets. Most researchers used these common materials to prepare slime robots. Now, discuss in detail about all these materials [1-4].

2.1.1 Polyvinyl Alcohol (PVA)

Polyvinyl alcohol (PVA) is a synthetic polymer having hydroxyl group(-OH), made from the polymerisation of vinyl acetate. The general formula of PVA is $[-CH_2-CH(OH)-]$ and it does not contain any ester or acetate groups after hydrolysis [5,6]. Considering PVA (polyvinyl alcohol) in the preparation of magnetic slime robots due to its several useful properties like viscoelastic in nature, water soluble and non-toxic in nature & reconfigurable and self-healing in nature [7].

2.1.2 Borax

Borax is sodium tetraborate decahydrate ($Na_2B_4O_7 \cdot 10H_2O$) have found great application in various fields of engineering, especially in biomedical, electronics and sensors, etc. Borax also plays an important role in the making of magnetic slime robots. It provides better mechanical properties and self-healing behaviour to magnetic slime robots [8].

2.1.3 Magnetic particles

Magnetic particles are also very important materials like borax and PVA (polyvinyl alcohol) because it makes robots to actuate in surrounding environments when externally magnetic force is applied to them. These magnetic particles are generally in the form of iron filings or neodymium powder [9]. These magnetic particles show strong magnetic properties and are embedded in the matrix of PVA and borax solution [10].

2.1.4 Magnets

A strong magnet, like neodymium magnets, is used in magnetic slime robots to control the movement through magnetic force. These magnets also help the robots to pull, push, or shape the slime from a distance; for these reasons, researchers prefer strong magnets rather than weak magnets, which can't exert enough force to move the magnetic slime robots [11, 12].

3. Basic concept, methodology and Design of Magnetic slime robots

The basic concept and design of magnetic slime robots are generally based on three basic categories. These categories include:

3.1 Non-Newtonian fluid matrix

In Fig. 1, the blue ellipse represents the non-Newtonian fluid. This non-Newtonian fluid is considered a base material, which behaves like a liquid when a gentle force is applied but can act more like a solid when a sudden impact or strong force is applied. According to Saikia et al., this viscoelastic nature of non-Newtonian fluid allows the robots to have flexible movement, adapt to changes in shape and the ability to grasp objects [13].

3.2 Embedded magnetic Particles

In Fig. 1, the embedded magnetic particles are represented by the red dotted particles. These particles can respond to the external magnetic field, which enables precise control of robot movements [4].

3.3 External magnetic fields

The black arrows represent the external magnetic field, which is shown in Figure 1. These external magnetic fields are applied to control the robot movements [4].

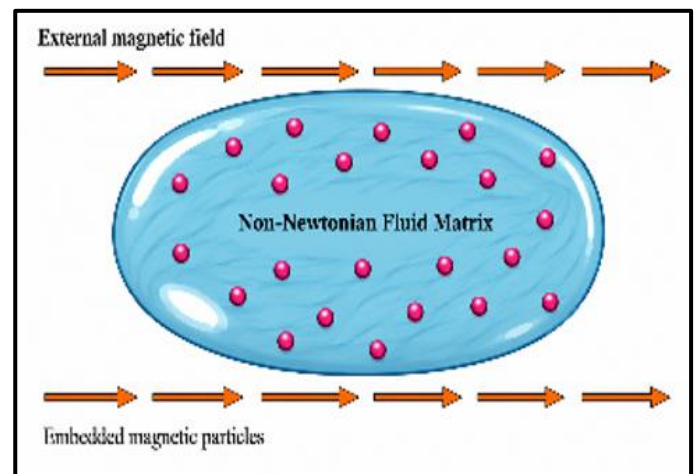


Figure 1: Schematic illustration of the basic concept and design of the magnetic slime robot [4].

4. Fabrication of magnetic slime robots

First, PVA is dissolved in water by heating at $90^{\circ}C$ for 3 hours, while a borax solution is prepared separately by dissolving borax in water. Both solutions are then mixed to form the slime base. Next, NdFeB magnetic powder is added and mixed thoroughly to ensure uniform distribution of the magnetic particles. If required, the prepared slime is coated with a thin layer of silicone oil or enclosed in a protective membrane to improve stability and biocompatibility. Finally, the magnetic slime is tested by applying an external magnet to evaluate its movement, stretching, splitting, rejoining, and ability to pick up small objects [14].

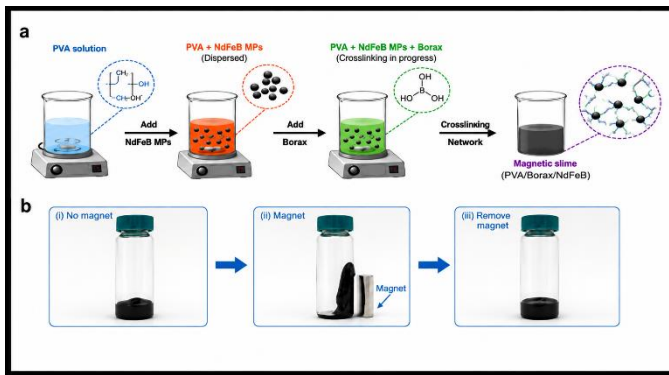


Figure 2: (a) Schematic illustration of the magnetic slime robot fabrication process, (b) Image of the fabricated magnetic slime robot [14].

4.1 Preparation layout of magnetic slime robot

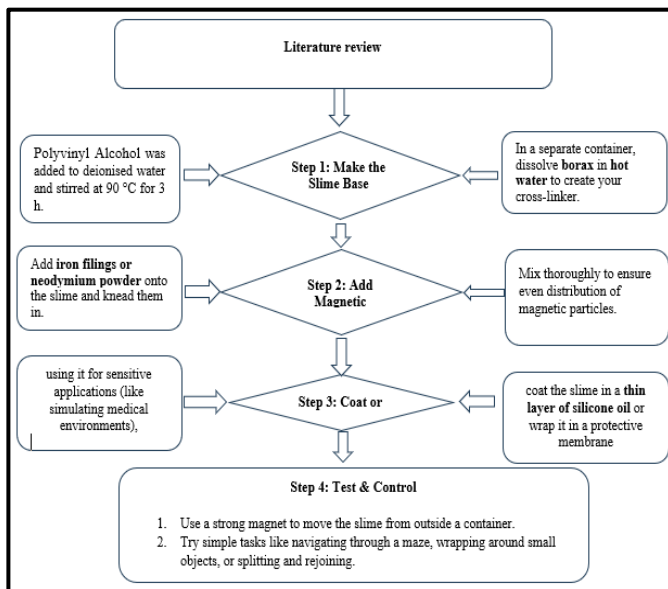


Figure 3: Schematic layout for the preparation of the magnetic slime robot.

5. Properties of Magnetic Slime

The slime robots are typically composed of polyvinyl alcohol, borax and magnetic particles (NdFeB), which are coated with silicon dioxide to minimise the toxicity of slime. This unique composition is responsible for providing the remarkable set of properties to magnetic slime robots.

5.1 Self-Healing

One of the most remarkable properties of magnetic slime robots is their self-healing ability. When cut into multiple pieces, the slime can rapidly reconnect and restore its functionality through the reversible hydrogen bonding between borate ions and hydroxyl (-OH) groups without any external stimulus, as shown in Figure 4(a). The healing process occurs within 1 s, and the repaired slime retains excellent plasticity and can be stretched up to 8.6 times its original length without failure at the healed region [14, 15]. Similarly, under

an external magnetic field, multiple cut pieces of magnetic slime autonomously reconnect and complete the healing process, as shown in Fig. 4(b).

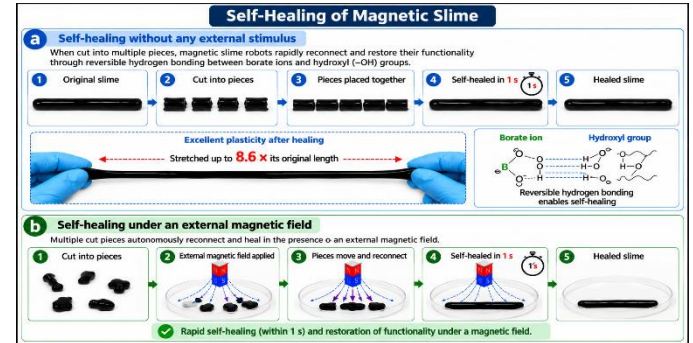


Figure 4: (a) Self-healing of damaged magnetic slime samples, demonstrating complete healing within 1 s, and (b) sequential images illustrating the self-healing process of the magnetic slime [15].

5.2 Controlled Manipulation/Deformability/Reconfigurability

The controlled manipulation, deformability, and reconfigurability of magnetic slime robots arise from their non-Newtonian fluid nature, allowing them to behave as either a liquid or a semi-solid depending on the applied force. The embedded magnetic particles enable the slime to deform under an external magnetic field by stretching, squeezing, curling, and engulfing objects. Its magnetic response can be adjusted by varying the magnetic particle content or the strength of the applied magnetic field [15,16]. Figure 5(a) shows that magnetic slime can use its curling mode to grasp objects after elongation. Xie et.al. have reported about curling operation with time will be able to make grasping possible for those species which live in long-range and restricted environments.

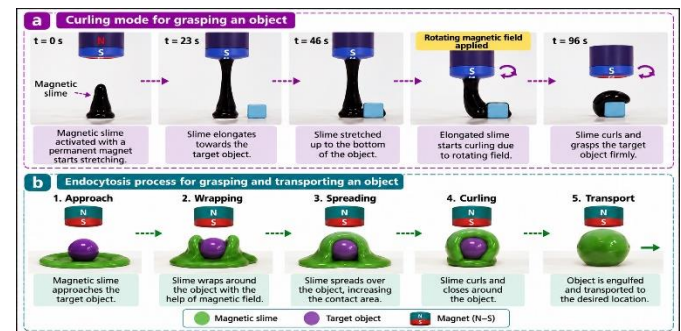


Figure 5: (a) Sequential images illustrating the curl operation mode of the magnetic slime robot over time, and (b) sequential images showing the endocytosis operation mode of the magnetic slime robot over time [16].

During the curling operation mode with time, when time $t = 0s$, the magnetic slime activated with a permanent magnet started stretching. After 46s, the magnetic slime stretched up to the bottom of the object. In such a case, if a rotating magnetic field is applied, the elongated magnetic slime will start curling and grabbing the target object as is evident from Figure 5(a).

Magnetic slime is also able to grasp and transport an object through the endocytosis process [16]. Magnetic slime can swallow the target object through wrapping, spreading and curling, successively, as is evident from Figure 5(b).

5.3 Environmental adaptability

Magnetic slime can pass through rugged terrain, porous media, and confined spaces with dimensions of at least 1.5 mm Figure 6(a). Magnetic slime can travel through narrow passages, pipes, maze-like structures, and rugged terrain. However, it takes 180 s to pass through a 1.5 mm channel. In an externally applied magnetic field, the increased percentage of magnetic particles improves both the magnetic sensitivity and deformability of magnetic slime. The mobility of magnetic slime is also demonstrated on hydrogel, metal, plastic, glass, silicon, silicon wafer, PDMS, and paper substrates Figure 6(b) [15-17].

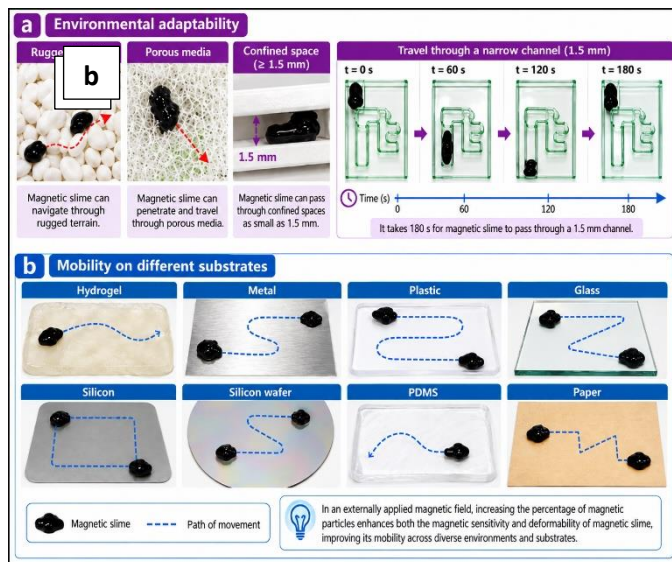


Figure 6: (a) Magnetic slime navigating through various complex environments, including narrow channels, confined tubes, complex mazes, and uneven substrates, and (b) movement patterns of the magnetic slime robot on different substrates [1].

5.4 Biocompatibility

Magnetic slime robots contain magnetic particles, which are toxic materials in nature; to make the slime robot biocompatible, researchers coat the magnetic particles with non-toxic materials such as silicon dioxide (SiO₂). The main aim of coating the particles is to make the slime robot safer for biomedical applications. This coating prevents the leakage of toxic particles into the body [17].

6. Application of magnetic slime robots in the real world

Magnetic slime robots have important applications in engineering and healthcare. Their unique properties make them useful for circuit repair, fault detection, neurological research, and targeted drug delivery [16,17]. The following sections discuss these applications in detail.

6.1 Electronics and Circuit Repair

Applications of magnetic slime robots are growing due to its self-healing, flexibility, and electroconductivity. The latter makes it suitable for use in different electronic gadgets. As a result of the electroconductivity of magnetic slime, it can be used as a circuit switch, as can be seen in Figure 7(a), which shows fabrication of three-way circuits that have made LED bulbs of different colours light up [18]. Circuit repair using magnetic slime robots is also addressed in this paper. In essence, the circuit repair process involves three main steps, namely stretching, spreading, and curling, as can be seen in Figure 7(b).

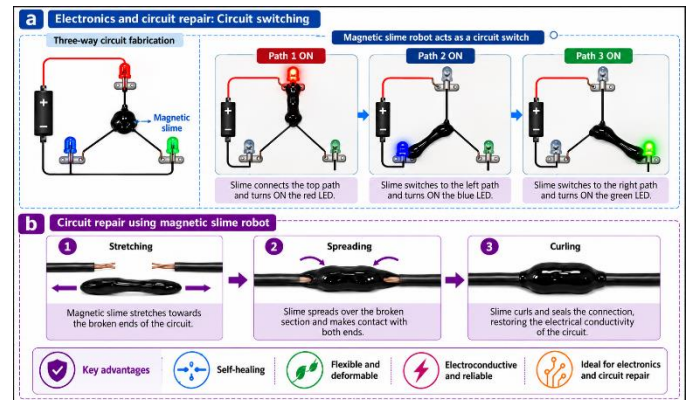


Figure 7: (a) Magnetic slime functioning as an electrical switch, and (b) magnetic slime used for electrical circuit repair [1].

6.2 Biomedical

Application of magnetic slime in the field of medical science has become more advanced due to its targeted drug delivery capabilities. The magnetic slime adheres to the affected parts of the body and serves as a targeted drug delivery system. If any foreign substance is present in the body, the slime robot begins to engulf and capture it, then drag it out of the body in the presence of an external magnetic field, as shown in Figure 8 [16-18].

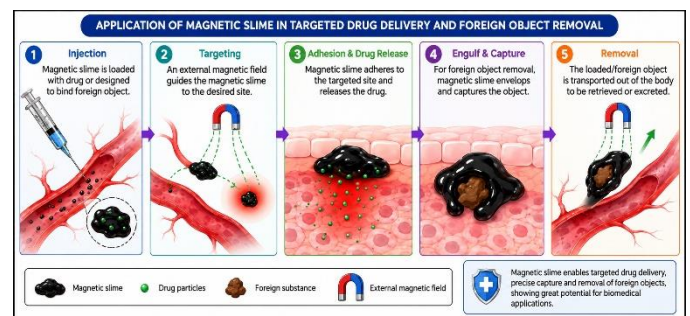


Figure 8: Targeted drug delivery using the magnetic slime robot [4].

6.3 Act as soft actuators and Sensors

Due to the self-healing, reconfigurability and conductivity properties of magnetic slime, act as a soft actuator and sensor. This paper also discusses the application of magnetic slime for detecting human body movements as shown in Figure 9. The

magnetic slimes were encapsulated in VHB tape directly on the skin of the human body to detect bending and extension behaviour, such as wrists, shoulders, fingers and elbows, etc. The detection of human body movement directly depends on the change in resistance value [19-21].

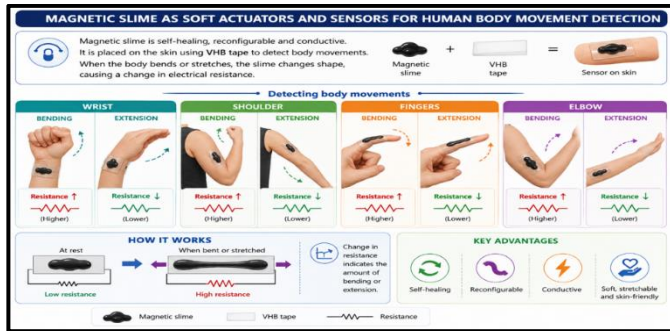


Figure 9 Detection of human body movements using the magnetic slime robot [1].

6.4 Art, Entertainment and Education

The applications of magnetic slime extend beyond engineering and medicine to arts, entertainment, and education. It is used in kinetic sculptures, interactive art, educational models, science projects, and toys, making it valuable for both creative and learning purposes [4,18-22].

7. Limitations of Magnetic Slime Robots

Magnetic slime robots offer significant advantages in medical, engineering, and other applications due to their unique properties, such as self-healing and reconfigurability, which distinguish them from conventional robots. However, they also face several limitations. The magnetic particles used in the slime are inherently toxic, posing safety concerns, particularly for targeted drug delivery. Although coating these particles can reduce toxicity, developing effective coating techniques remains a challenge. In addition, achieving precise motion control using external magnetic fields is still difficult. Despite these limitations, ongoing research aims to improve the safety and controllability of magnetic slime robots [20, 23, 24].

8. Conclusion

This paper reviews the preparation, properties, applications, and limitations of magnetic slime robots. As a type of soft robot, magnetic slime exhibits superior deformability compared to elastomer-based robots due to its non-Newtonian fluid nature. It possesses unique properties such as self-healing, reconfigurability, controlled manipulation, environmental adaptability, and biocompatibility. Its major applications include targeted drug delivery, electronic circuit repair, human motion detection, and foreign object retrieval. However, challenges related to stability, biocompatibility, and precise motion control remain. Ongoing research is focused on overcoming these limitations and expanding the potential applications of magnetic slime robots.

Credit to author contribution statement

Uttam Kumar: Conceptualization, Methodology, Investigation, Formal analysis, Writing, Reviewing and editing.

Shailesh Kumar Pandey: Methodology, Writing, Reviewing and editing, Project supervision, Data collection.

Rehan Khan: Conceptualization, Data curation, Writing and reviewing, Project supervision.

Abhishek Singh: Methodology, Data curation, Investigation, Formal analysis.

Sameer Kumar: Methodology, Data collection, Investigation, Formal analysis

Declaration of competing interests

The authors declare that they have no known competing financial or personal relationships that could have influenced the results reported in this review article.

Funding

This research received no grant from any funding agency in public, commercial, or not-for-profit sectors.

Availability of data and materials

Not applicable

Ethical approval

All authors have approved the manuscript and agreed to submit it as a review article for possible publication in the National Symposium (Hybrid Mode) on Intelligent Manufacturing, Additive Technologies, and Sustainable Engineering (IMATSE-2026). Further, the corresponding author would like to undertake that this manuscript is not under consideration by another journal.

Acknowledgement

The Authors would like to acknowledge the institute, Dr B R Ambedkar National Institute of Technology, Jalandhar, for providing the necessary facilities and resources for this article.

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Cite this article as: Uttam Kumar, Shailesh Kumar Pandey Rehan Khan, Abhishek Singh, Sameer Kumar, Recent Advances in Magnetic Slime Robots: Materials, Self-Healing, Reconfigurability, and Multifunctional Applications, International Journal of Research in Engineering and Innovation, 10 (5), (2026), 225-230. <https://doi.org/10.36037/IJREI.2026.10507>