

Ferrofluid and Its Application in Wound Healing

Eldar Osmonov

Oxford International School, Mira Avenue 153/1, Bishkek, Chuyskaya Oblast, 720040, Kyrgyzstan; jigin2009@gmail.com

ABSTRACT: This study examined the effects of ferrofluids—suspensions of magnetic nanoparticles—on tissue regeneration in *Lumbriculus Variegatus*, an earthworm known for its regenerative ability. Ferrofluids are considered promising in biomedical fields due to their responsiveness to magnetic fields, but their biocompatibility in regenerative systems remains unclear. In this experiment, worms were divided into five groups and exposed to varying concentrations of ferrofluid, with or without magnetic field influence. Regeneration was monitored over six days using behavioral activity scoring and tail regrowth measurements. The results showed a clear dose-dependent decline in regeneration among ferrofluid-treated groups, especially at higher concentrations. The control group exhibited the most robust recovery, while worms exposed to both ferrofluid and magnetic fields showed reduced regrowth and movement. Reproductive inhibition was also observed in all ferrofluid-treated worms. These findings suggest potential toxicity or cellular disruption caused by ferrofluid exposure. While ferrofluids have biomedical potential, this study emphasizes the need for further research on their long-term effects, safety, and interaction with complex biological systems.

KEYWORDS: Biomaterials, Biomaterials and Regenerative Medicine, Regeneration, Earthworms, Ferrofluid.

Introduction

Background information shows why your research is necessary and important. Summarize literature on related work. State the goal of your research and how it differs from current literature at the end of the introduction section. Magnetic nanoparticles (MNPs) have attracted significant attention in recent years due to their multifunctionality and unique behavior under external magnetic fields. Their nanoscale size and high surface area-to-volume ratio,¹ combined with their superparamagnetic properties,² allow precise manipulation within biological systems. These traits have positioned MNPs at the forefront of biomedical innovation, enabling advances in targeted drug delivery,³ magnetic resonance imaging (MRI) enhancement, tissue engineering,⁴ and hyperthermia-based cancer therapy.⁵

Among their many biomedical uses, one particularly promising application of MNPs is in wound healing and regenerative medicine. Magnetic fields have been shown to influence critical biological processes such as cell migration and proliferation. Additionally, when integrated into biocompatible systems like ferrofluids, MNPs can deliver these magnetic stimuli in a controlled and localized fashion.⁵

Ferrofluids—stable liquid suspensions of magnetic nanoparticles—are especially appealing because of their ability to be directed by external magnets. This responsiveness allows researchers to guide their movement through tissues,⁶ create physical cues for cellular alignment, and apply localized magnetic stimulation for tissue regeneration.⁴ Some studies have also demonstrated that ferrofluids may exhibit antimicrobial properties, reducing bacterial growth at wound sites.⁷

These features make ferrofluids strong candidates for non-invasive therapies, offering alternatives to traditional surgical or pharmacological approaches.⁴ Their adaptability also makes them suitable for integration with hydrogels, scaffolds,

and other delivery platforms,⁸ supporting long-term tissue repair strategies.

To examine the biological impact of ferrofluids on regeneration, *Lumbriculus Variegatus* was employed as an earthworm commonly used in ecotoxicological and developmental studies.⁹ This species is well-suited for regeneration research due to its robust regenerative ability,¹⁰ transparent body for microscopic analysis, and the ethical advantages it offers over vertebrate models.

This study investigated whether exposure to ferrofluids affects the tail regeneration process in *Lumbriculus Variegatus*. This study was done by comparing regeneration metrics—such as tissue length and morphology—under varying concentrations of ferrofluids and controlled magnetic field exposure.

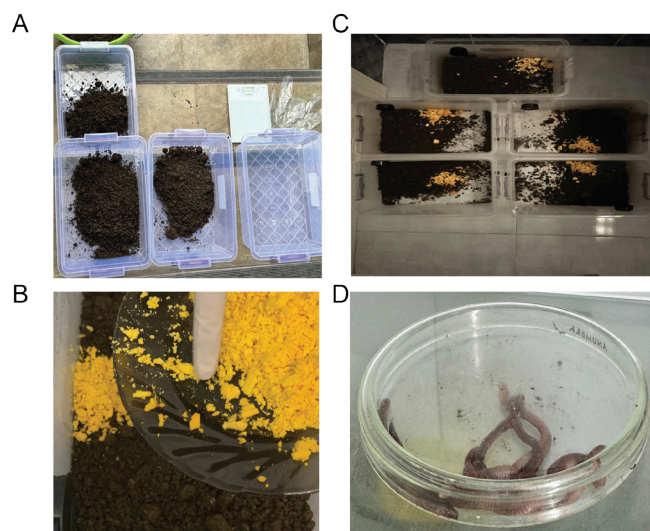


Figure 1: Preparation for the experiments. (A) Preparations of the boxes for 500 g of soil. (B) Feeding worms with 15 g egg yolk. (C) Prepared boxes with 15 g egg yolks. (D) Five worms in a refrigerator at 5 degrees Celsius since cold temperatures work for them as an anesthesia.

Methods

Earthworm care:

For this experiment, earthworms of similar size were housed in plastic containers measuring no less than 30 cm × 20 cm × 15 cm, each filled with 0.5 kg of pesticide-free, nutrient-rich soil to simulate a natural environment as seen in Figure 1A.¹¹ The containers were kept at a stable temperature between 13–27 °C, and dim yellow lighting was used to minimize external stress on the worms. Humidity levels were maintained by adding 70–100 mL of deionized water daily, using digital humidity and temperature sensors to monitor consistency.⁹ Earthworms were fed once per week with 15 g of hard-boiled egg yolk only (Figure 1B, C), based on nutritional support for regeneration.¹² Uneaten food was removed after four days to prevent bacterial contamination in the substrate.¹¹

Wound induction:

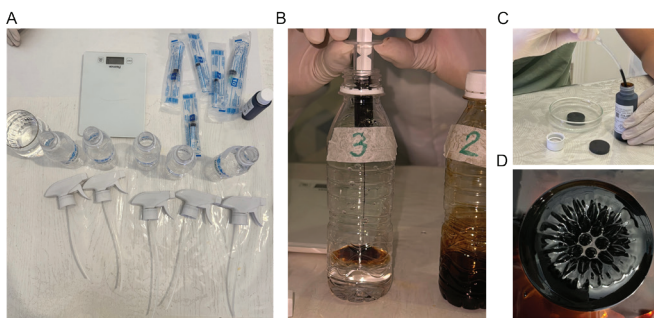


Figure 2: Experimentations with ferrofluid and preparation of the solution. (A) Equipment needed to create different ferrofluid concentrations. (B) Mixing ferrofluid concentrations. Concentration 1 is 0,75 ml ferrofluids+50ml of water in 500g of soil. Concentration 2 is 1.65 ml of ferrofluids + 50ml of water in 500g of soil. Concentration 3 is 3 ml of ferrofluids + 50ml of water in 500g of soil. Concentration 4 is 1.65 ml ferrofluids + 50ml of water in 500g of soil+external magnet. Concentration 5 is 50ml of water in 500g of soil. (C) Experimenting with ferrofluid. (D) Ferrofluid influenced by a magnet.

To apply an anesthetic effect, the worms were put into the fridge, as seen in Figure 1D. To introduce wounds, each *Lumbricus Variegatus* was carefully cut transversely just behind the clitellum, preserving the anterior part for observation, as this segment retains regenerative ability.¹³ All worms were observed daily over seven days, at the same time each day (22:30), to monitor tissue regeneration, changes in behavior, and any discoloration.

Treatment preparation:

To prepare the ferrofluid treatment as seen with the equipment in Figure 2A, a concentration of 3.3 μL of ferrofluid per gram of soil was mixed thoroughly by hand stirring to ensure even distribution without agitating the worms (Figure 2B). Earthworms were divided into five experimental groups, each containing five individuals: a control group receiving only water, a low concentration group with 1.5 $\mu\text{L/g}$ ferrofluid, a medium concentration group with 3.3 $\mu\text{L/g}$, a high concentration group with 6 $\mu\text{L/g}$, and a final group exposed to 3.3 $\mu\text{L/g}$ ferrofluid along with a small external neodymium magnet (1 cm diameter × 0.5 cm height) placed outside the container wall.

Results and Discussion

Experiment with ferrofluids:



Figure 3: Manipulations with worms, like cutting and measuring. (A) Cutting a worm using sterilized blade (B) Rating 1 out of 5 activity rate where 1 is move very little, only when needed to eat (C) Rating 2 out of 5 activity rate where 2 is moving around the box or paper when measured (D) Rating 3 out of 5 activity rate where 3 is moving faster, active, do not move only when they are sleeping (E) Rating 4 out of 5 activity rate where 4 is moving almost in every situation (F) 5 out of 5 activity rate where 5 is always moving, not sleeping at all, will jump if touched.

In Figure 2C, a small volume of ferrofluid was introduced into a petri dish. A strong magnet was placed beneath the dish. Initially, the ferrofluid appeared as a dense black liquid. However, upon approaching the magnetic field, morphological changes were observed. In Figure 2D, the ferrofluid exhibits distinct spiked formations. These patterns resulted from the alignment of magnetic nanoparticles within the fluid in response to the external magnetic field. When the magnet was repositioned, the spikes reoriented accordingly, visually demonstrating the ferrofluid's dynamic response to magnetic influence in real time.

Table 1: Length of individual worm (in cm) Group 1 in six days. D is day.

Worm	Before experiment	After cut	D1	D2	D3	D4	D5	D6
1	5.3	3.8	3.9	4.1	4.2	4.2	4.3	4.4
2	6.4	4.4	4.5	4.7	4.8	4.8	4.8	4.9
3	5.4	4	4	4	4	4.2	4.3	4.5
4	6.2	4.1	4.2	4.3	4.4	4.6	4.8	4.9
5	5.4	4	4.1	4.2	4.2	4.2	4.3	4.3

Table 2: Length of individual worm (in cm) Group 2 in six days. D is day.

Worm	Before experiment	After cut	D1	D2	D3	D4	D5	D6
1	6.3	4.3	4.3	4.4	4.5	4.5	4.6	4.6
2	6	4.2	4.3	4.5	4.6	4.7	4.9	4.9
3	6.4	4.9	5	5.1	5.2	5.2	5.3	5.3
4	5.7	3.7	3.8	3.9	4	4.1	4.3	4.4
5	6.6	4.6	4.6	4.6	4.7	4.8	5	5

Table 3: Length of individual worm (in cm) Group 3 in six days. D is day.

Worm	Before experiment	After cut	D1	D2	D3	D4	D5	D6
1	6.8	4.7	4.7	4.7	4.8	4.9	4.9	X
2	6.4	4	4	4	4	4	4	4
3	6	4	4.2	4.2	4.2	4.2	4.2	4.2
4	6.3	4.7	4.7	4.7	4.8	4.9	5.1	5.1
5	7	4	4.2	4.3	4.4	4.5	4.6	4.6

Table 4: Length of individual worm (in cm) Group 4 in six days. D is day.

Worm	Before experiment	After cut	D1	D2	D3	D4	D5	D6
1	6	4.1	4.2	4.2	4.2	4.2	4.3	4.5
2	6.9	5	5	5.2	5.3	5.7	6	X
3	6.3	5	5	5	5.1	5.1	5.2	5.2
4	7	4.5	4.5	4.5	4.5	4.5	4.6	4.6
5	7.3	4.5	4.5	4.5	4.5	4.6	4.8	5

Table 5: Length of individual worm (in cm) Group 5 in six days. D is day.

Worm	Before experiment	After cut	D1	D2	D3	D4	D5	D6
1	7.4	5	5	5.1	5.2	5.2	5.2	5.2
2	5.3	3.1	3.3	3.4	3.6	3.9	4.3	4.3
3	6.1	3.9	4	4.2	4.4	4.7	4.9	5
4	5.8	3.5	3.6	3.7	3.8	4.2	4.5	4.6
5	5.2	3.9	4	4.1	4.3	4.5	4.9	5

Measurement of Worm Activity and Regeneration:

In Figure 3A, surgical incisions were made using a sterilized blade to initiate the regeneration phase. The objective was to assess the impact of physical injury on both behavioral activity and regenerative capacity over subsequent days. Post-incision, activity levels were recorded and assigned values on a scale from 1 to 5, based on observable movement.

In Figure 3B, minimal spontaneous movement was noted. Only weak responses were elicited upon direct tactile stimulation, resulting in an activity score of 1. Figure 3C displayed slightly increased motility; the subject exhibited occasional movement and directional changes, corresponding to a score of 2. In Figure 3D, moderate, stimulus-responsive movement was observed, leading to a rating of 3. Figure 3E showed higher autonomous activity, with the worm moving without external prompting and remaining mostly active; this behavior was scored as a 4. In Figure 3F, continuous, unprovoked, and rapid movement was documented, warranting the maximum activity rating of 5.

In addition to behavioral scoring, physical regrowth was quantitatively assessed over six days, as shown in Tables 1 through 5. In Table 1, all subjects survived the observation period. Regeneration proceeded steadily; for example, Worm 2 measured 4.4 cm post-incision and reached 4.9 cm by Day 6, with consistent daily increases of approximately 0.1 cm.

Table 2 reflected similar trends, with complete survival and slightly accelerated regrowth in most specimens. Notably, Worm 3 demonstrated enhanced regeneration, growing from 4.9 cm to 5.3 cm.

Table 3 presents more variable outcomes. While most subjects displayed satisfactory regrowth, Worm 1 did not survive past Day 5, despite normal development up to that point. Conversely, Worm 4 showed robust recovery, increasing from 4.7 cm to 5.1 cm.

Table 4 also recorded a mortality: Worm 2 expired prior to Day 6 but had exhibited strong growth up to 6.0 cm by Day 5. Remaining subjects showed modest but stable increases, particularly Worms 3 and 4, which followed a consistent regeneration trajectory without irregularities.

Table 5 yielded the most uniform and reliable results. No mortality occurred, and growth patterns were progressive and uninterrupted across all specimens. Worm 3 exhibited the most pronounced increase, from 3.9 cm to 5.0 cm, with others demonstrating similar trends.

Despite multiple publications reporting that ferrofluids may enhance wound healing or tissue regeneration,^{14,15} the findings from this study did not support those conclusions, suggesting that exposure to ferrofluids would increase regeneration rates in *Lumbriculus variegatus*. However, the findings from this study did not support that hypothesis.

As shown in Figure 4, regeneration rates were noticeably suppressed in all groups treated with ferrofluid, especially at higher concentrations. Group 3 (3 mL) demonstrated the weakest regeneration trend, with barely any growth observed beyond Day 2. Group 4 (1.65 mL + magnet) also showed reduced regrowth, suggesting that the presence of a magnetic field may intensify the inhibitory effects of ferrofluid exposure.

By contrast, Group 5 (control) exhibited the most robust and consistent regeneration over the six days, with the highest normalized average length on Day 6. Groups 1 and 2, exposed to lower concentrations of ferrofluid (0.75 mL and 1.65 mL, respectively), showed intermediate results. While slight increases in length were observed, they lagged significantly behind the control. This dose-dependent decline in regenerative performance indicates a likely biological sensitivity to ferrofluid concentration.

Furthermore, reproductive inhibition was observed in all ferrofluid-treated groups. No offspring were recorded, in contrast to the control group, which demonstrated both tissue regrowth and successful reproduction. This finding supports previous evidence that ferrofluids may interfere with cellular or reproductive systems. The possibility that magnetic nanoparticles disrupt internal signaling or cellular integrity at the reproductive level should be explored in future investigations.

Overall, the data from Figure 4 visually emphasize that the presence and concentration of ferrofluid—particularly in conjunction with magnetic fields—correlates with impaired biological recovery and function. These findings contrast with earlier optimistic assessments and highlight the need for further research into the biocompatibility of ferrofluids under varying environmental and physiological conditions.

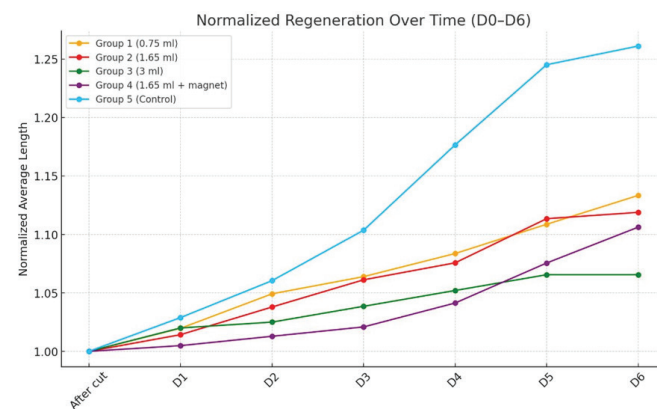


Figure 4: Normalized average graph that shows regeneration of 5 groups of worms with various concentrations of ferrofluid over 6 days.

Limitations:

This study had several limitations. First, it used only one model organism, *Lumbriculus Variegatus*, which, while helpful for studying regeneration, does not reflect the complexity of cells or immune responses in more advanced organisms like zebrafish or mice. Second, because of limited resources, only one type of commercially available ferrofluid was used. This made it impossible to compare how different ferrofluid types (with different coatings or magnetic strengths) might affect results. Third, the study didn't use advanced tools like fluores-

cence microscopy or gene expression analysis, which could have helped show how cells responded at a deeper level. Fourth, the experiment lasted only six days, so long-term effects like reproduction or full organ recovery were not studied. Fifth, since the project was done at home without lab-grade equipment, it was not possible to measure more complex biological details.

Future studies should use more advanced organisms like zebrafish, axolotls, or mice, which are often used in regeneration research. Testing ferrofluids with safer coatings like PEG, silica, or dextran could also reduce harmful effects and make them more suitable for medical use. Using better imaging tools and running longer experiments would help us understand how ferrofluids interact with living tissues over time.

■ Conclusion

This study examined the effects of ferrofluids on tissue regeneration using *Lumbriculus variegatus*, a model organism known for its high regenerative capacity. Ferrofluids, composed of magnetic nanoparticles, are widely regarded as promising tools in biomedical applications due to their ability to respond to magnetic fields, potentially guiding healing or stimulating growth. Previous research suggested their utility in wound healing, but their biological safety and functional outcomes remain under investigation.

In this experiment, *Lumbriculus variegatus* were wounded and divided into five groups, receiving different concentrations of ferrofluid—with or without magnetic field exposure—while one group served as a control. Conditions such as soil type, lighting, temperature, and feeding were carefully controlled, and regeneration was monitored through both behavioral activity scoring and tail regrowth measurements over six days.

The results showed a clear dose-dependent decline in regeneration among all ferrofluid-treated groups. Higher concentrations of ferrofluid, especially when combined with an external magnet, led to reduced or delayed regeneration. In contrast, the control group demonstrated the most consistent and robust regrowth. Behavioral activity mirrored these findings, with treated groups exhibiting less spontaneous movement, suggesting possible physiological stress or disruption.

The discussion highlighted that, contrary to previous studies, ferrofluids in this context did not promote regeneration—instead, they impaired it. The study also observed reproductive inhibition in all treated groups, supporting concerns about ferrofluid safety in biological systems. Magnetic fields may have intensified these effects, further complicating the role of ferrofluids in therapeutic use. This calls into question the assumption that their physical responsiveness automatically equates to biological benefit.

A major limitation was that the experiment only used one species and did not track ferrofluid uptake at the cellular level. Future research should explore how ferrofluids interact with internal tissues using imaging and molecular tools, test across other organisms, and investigate long-term effects such as reproductive damage. Developing ferrofluid formulations with safer coatings may also help reduce toxicity and better support regenerative applications.

In conclusion, this study challenges optimistic assumptions about ferrofluid-assisted regeneration. Further research is necessary to evaluate their safety, optimize formulations, and clarify their mechanisms of action in both short- and long-term biomedical use.

■ Acknowledgments

I would like to express my special thanks of gratitude to my mentor, Trinity Tat, and Indigo Research for their invaluable support and guidance throughout this process. I also want to thank my mom for providing me with the necessary resources, equipment, and a comfortable environment. I attest that the ideas, graphics, and writing in this paper are entirely my own.

■ References

1. *Magnetic nanoparticles*. Wikipedia. https://en.wikipedia.org/wiki/Magnetic_nanoparticles.
2. *Superparamagnetism*. Wikipedia. <https://en.wikipedia.org/wiki/Superparamagnetism>.
3. *Magnetic drug delivery*. Wikipedia. https://en.wikipedia.org/wiki/Magnetic_drug_delivery.
4. Lu, A.-H.; Salabas, E. L.; Schüth, F. Magnetic Nanoparticles: Synthesis, Protection, Functionalization, and Application. *Chem. Soc. Rev.* **2007**, *36* (12), 2821–2834. <https://doi.org/10.1039/B618799H>.
5. Dutz, S.; Hergt, R. A Review of Magnetic Nanoparticles for Biomedical Applications: Synthesis and Functionalization. *APL Materials* **2024**, *12* (1), 010601. <https://doi.org/10.1063/5.0133927>.
6. Alessandro Surpi; Shelyakova, T.; Murgia, M.; Rivas, J.; Piñeiro, Y.; Greco, P.; Fini, M.; Valentin Alek Dediu. Versatile Magnetic Configuration for the Control and Manipulation of Superparamagnetic Nanoparticles. *Scientific Reports* **2023**, *13* (1). <https://doi.org/10.1038/s41598-023-32299-9>.
7. *Magnetic nanoparticles – Potential applications*. Wikipedia. https://en.wikipedia.org/wiki/Magnetic_nanoparticles#Potential_applications.
8. R. Hernández; J. Sacristán; L. Asín; Torres, T. E.; Ibarra, M. R.; Goya, G. F.; Mijangos, C. Magnetic Hydrogels Derived from Polysaccharides with Improved Specific Power Absorption: Potential Devices for Remotely Triggered Drug Delivery. *The Journal of Physical Chemistry B* **2010**, *114* (37), 12002–12007. <https://doi.org/10.1021/jp105556e>.
9. *Earthworm*. Wikipedia. <https://en.wikipedia.org/wiki/Earthworm>.
10. Agatz, A.; Miles, M.; Roeben, V.; Schad, T.; Van Der Stouwe, F.; Zakharova, L.; Preuss, T. G. Evaluating and Explaining the Variability of Honey Bee Field Studies across Europe Using BEEHAVE. *Environmental Toxicology and Chemistry* **2023**, *42* (8), 1839–1850. <https://doi.org/10.1002/etc.5678>.
11. Canada, E. and C. C. *Biological test method: Tests for measuring avoidance behaviour or reproduction of earthworms (Eisenia andrei or Dendrodrius rubidus) exposed to contaminants in soil*. <https://www.canada.ca/en/environment-climate-change/services/wildlife-research-landscape-science/biological-test-method-publications/avoidance-behaviour-reproduction-earthworms-contaminants-soil.html>.
12. Scherer, C.; Figueiredo Neto, A. M. Ferrofluids: Properties and Applications. *Brazilian Journal of Physics* **2005**, *35* (3a), 718–727. <https://doi.org/10.1590/s0103-97332005000400018>.
13. Martinez Acosta, V. G.; Arellano-Carbajal, F.; Gillen, K.; Tweeten, K. A.; Zattara, E. E. It Cuts Both Ways: An Annelid Model System for the Study of Regeneration in the Laboratory and in

- the Classroom. *Frontiers in Cell and Developmental Biology* **2021**, *9*, 780422. <https://doi.org/10.3389/fcell.2021.780422>.
14. *The Impact of Ferrofluid on Innovation in Biomedical Engineering*. Patsnp Eureka. <https://eureka.patsnap.com/report-the-impact-of-ferrofluid-on-innovation-in-biomedical-engineering> (accessed 2026-02-20).
15. Wang, M.; Deng, S.; Cao, Y.; Zhou, H.; Wei, W.; Yu, K.; Cao, Y.; Liang, B. Injectable Versatile Liquid-Solid Transformation Implants Alliance Checkpoint Blockade for Magnetothermal Dynamic-Immunotherapy. *Materials Today Bio* **2022**, *16*, 100442. <https://doi.org/10.1016/j.mtbio.2022.100442>.

■ Author

Eldar Osmonov is an incoming senior at Oxford International School in Bishkek. He is interested in bioengineering and biomedical science. Throughout the study of ferrofluid and its application in wound healing, he understood concepts of the fields of study he is interested in. In the future, he wants to major in bioengineering, focusing on bioinstrumentation, cellular therapy, and genome editing.