ISSN E 2959-3751
ISSN P 2959-3743

RICOS BIOLOGY JOURNAL

Vol. 4, no. 3
March, 2026

https://ricosbiology.net
https://ricospublisher.us
info@ricosbiology.net

Ricos Biology Journal, March, 2026, Vol. 4 (3) 1-35.
www.ricosbiology.net/Vol.4(3)/March-2026/1-35

RESEARCH ARTICLE
Open Access

Table of contents

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 1-6.
doi: https://doi.org/10.33687/ricosbiol.04.03.109

Educational Note

Missiles and Microbes: How the Amoxicillin–Clavulanic Acid Synergy Mirrors a Coordinated Iranian–Hezbollah Strike

Abouelhag H. A.

Microbiology and Immunology Dept., National Research Centre, Dokki, Egypt, 12622.

Received: 08-03-2026 **Accepted:** 22-03-2026 **Published online:** 30-03-2026
DOI: https://doi.org/10.33687/ricosbiol.04.03.109

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Abstract

The principles governing biological systems often mirror those observed in human geopolitics, strategy, and warfare. This review examines the synergistic action of amoxicillin and clavulanic acid against Gram-negative bacteria as a paradigmatic example of such mirroring. Here, biology presents a smaller-scale diagram of a larger-world strategic concept: a combined-arms offensive where one component neutralizes enemy defenses, enabling a second component to deliver the decisive strike with enhanced efficiency. Amoxicillin acts as the primary ordnance, while clavulanic acid functions as a counter-defense system—analogous to a coordinated missile strike involving Iranian precision-guided munitions and Hezbollah electronic warfare assets. Crucially, this synergy achieves bactericidal outcomes at lower individual concentrations, in shorter time, and at reduced overall cost—mirroring real-world military efficiency where coordinated assets minimize expenditure and maximize speed. This article is designed as an illustrative learning tool, demonstrating that complex microbiological interactions can be understood through parallels with real-world events, and that the logic of overcoming resistance is universal, whether in a bacterial cell or on a broader strategic stage.

Keywords: Amoxicillin, Clavulanic Acid, Beta-Lactamase Inhibitors, Gram-Negative Bacteria, Synergy, Antimicrobial Resistance, Cost-Effectiveness, Geopolitical Analogy, Microcosm, Pedagogical Illustration

1. Introduction: Biology as a Mirror of the Larger World

Throughout history, patterns of conflict, cooperation, and strategy observed in human affairs have often found echoes in the natural world. Biology, in its relentless competition for survival, frequently operates as a smaller diagram of the larger world—a microcosm where the same principles of defense, offense, strategic alliance, and resource optimization play out at a microscopic scale. This review adopts such a perspective, using the well-characterized synergy between amoxicillin and clavulanic acid as an illustrative case. Our objective is not merely to describe the biochemical mechanisms but to present them through a pedagogical lens: what happens in biology is a scaled-down reflection of what happens in real-world geopolitics. By drawing explicit parallels to a coordinated military operation—specifically, a scenario involving Iranian precision-guided missiles and Hezbollah counter-defense systems—we provide a framework that makes the science more accessible and memorable. Moreover, we emphasize that the synergistic effect yields practical benefits: it allows target destruction at lower concentrations of each agent, reduces the time required to achieve kill, and lowers the overall economic cost. These benefits are themselves microcosmic representations of strategic efficiency in the larger world. This article thus serves as a learning illustration, demonstrating that the logic of synergistic action transcends scales.

2. The Biological Microcosm: Mechanisms of Synergy

2.1 Amoxicillin: The Direct Strike Asset

Amoxicillin is a broad-spectrum beta-lactam antibiotic that exerts its bactericidal effect by inhibiting penicillin-binding proteins (PBPs) located on the inner bacterial membrane. PBPs catalyze the transpeptidation reaction required for cross-linking peptidoglycan strands, which provide structural integrity

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg

Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net
© 2026 Copyright by the Author
Scilit

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 1-6.
doi: https://doi.org/10.33687/ricosbiol.04.03.109

to the bacterial cell wall. Inhibition of PBPs disrupts cell wall synthesis, activates autolytic enzymes, and leads to osmotic lysis (Tipper & Strominger, 1965; Waxman & Strominger, 1983). In the microcosm, amoxicillin functions as the primary destructive force—the ordnance designed to eliminate the target.

2.2 Clavulanic Acid: The Counter-Defense System

Clavulanic acid is a naturally occurring beta-lactamase inhibitor produced by *Streptomyces clavuligerus*. It possesses negligible antibacterial activity on its own but acts as a "suicide inhibitor" of serine beta-lactamases, the primary defense mechanism produced by resistant Gram-negative bacteria. Clavulanic acid forms a stable, inactivated acyl-enzyme complex, irreversibly blocking the active site of these enzymes (Reading & Cole, 1977; Drawz & Bonomo, 2010). By neutralizing this defense, clavulanic acid clears a path for amoxicillin to reach its PBP targets. In this small-scale diagram, it serves as the countermeasure that disables the enemy's interception capabilities.

2.3 Synergy: A Combined-Arms Doctrine

The combination—co-amoxiclav—embodies a strategic principle: simultaneous deployment of a primary weapon and a dedicated countermeasure. Used alone, amoxicillin fails against beta-lactamase producers; used alone, clavulanic acid achieves no bacterial kill. Only together do they achieve a synergistic effect greater than the sum of their parts (Ball, 2000; Finlay et al., 2003). This synergy is quantifiable through fractional inhibitory concentration (FIC) indices, where values below 0.5 indicate true synergy (Odds, 2003).

3. Synergy in Action: Lower Concentrations, Shorter Time, Reduced Cost

3.1 Achieving the Target at Lower Concentrations

One of the most clinically significant outcomes of synergy is the reduction in the concentration of each agent required to achieve bacterial killing. In the absence of clavulanic acid, amoxicillin minimum inhibitory concentrations (MICs) for beta-lactamase-producing Gram-negative strains can exceed 256 mg/L. When combined with clavulanic acid at fixed ratios (typically 2:1 or 4:1), the MIC of amoxicillin often drops to ≤8 mg/L, a 32-fold or greater reduction (Barry et al., 1984; Fuchs et al., 1986). This concentration-sparing effect reduces the risk of dose-dependent toxicity and minimizes selective pressure for resistance (Geddes et al., 2007).

In the real-world analogy, this corresponds to a coordinated military strike where counter-defense assets (clavulanic acid) suppress enemy air defenses, allowing the primary strike force (amoxicillin) to achieve its objective with fewer munitions. The "lower concentration" mirrors the reduced number of missiles needed when defenses are neutralized—a hallmark of strategic efficiency.

3.2 Shorter Time to Bacterial Destruction

Synergy also accelerates the rate of bacterial killing. Time-kill curve studies demonstrate that co-amoxiclav achieves a ≥3-log10 reduction in colony-forming units within 4–6 hours against beta-lactamase-producing strains, whereas amoxicillin alone shows no significant killing over 24 hours (White et al., 1991; Smith et al., 1998). The rapid onset is attributed to the immediate inactivation of beta-lactamases by clavulanic acid, allowing amoxicillin to access PBPs without delay. In the geopolitical metaphor, this represents the speed advantage of a combined-arms operation: disabling the enemy's radar and air defense before the primary strike ensures that the target is destroyed swiftly, reducing the window for counter-moves or reinforcement.

3.3 Cost-Effectiveness: Economic Synergy

The economic implications of synergy are substantial. By lowering the required doses and shortening treatment duration, co-amoxiclav reduces direct drug costs, hospitalization time, and the burden of adverse events. Pharmacoeconomic analyses have shown that empirical use of co-amoxiclav for community-acquired pneumonia and complicated urinary tract infections results in lower total healthcare costs compared to alternative regimens or sequential monotherapies (Davey et al., 1996; Garau et al., 2003). Moreover, the prevention of treatment failure—which would necessitate more expensive second-line or intravenous agents—adds to cost savings.

In the larger world, this mirrors the economic logic of coalition warfare: pooling complementary assets (counter-defense and strike) achieves the objective at lower overall expenditure than deploying overwhelming

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN **2959-3751(*E*)**, **2959-3743**(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 1-6.
doi: https://doi.org/10.33687/ricosbiol.04.03.109

force without coordination. The "cost" in biology (drug production, healthcare resources) is analogous to the economic cost of military operations.

4. Illustration: Mapping the Biological Microcosm to the Larger World

To concretize this learning illustration, we map the biological components onto a real-world geopolitical scenario. The analogy is structured to show that the same logic governing bacterial resistance, synergy, and efficiency governs strategic conflicts on a larger scale.

Biological Microcosm (Gram-Negative Infection)	**Larger-World Analogy (Geopolitical Conflict)**
Gram-negative bacterial cell	A fortified military installation
Beta-lactamase enzymes in periplasm	Surface-to-air missile batteries (air defense system)
Amoxicillin alone	Primary strike without suppression of defenses—likely intercepted
Amoxicillin	Iranian precision-guided missile (primary ordnance)
Clavulanic acid	Hezbollah electronic warfare / counter-defense missile
Synergy outcomes	**Corresponding strategic advantages**
Lower amoxicillin MIC (concentration sparing)	Fewer munitions needed after air defense neutralization
Faster killing (shorter time to sterilization)	Rapid mission completion before enemy can adapt
Reduced cost (pharmacoeconomic benefit)	Lower total expenditure through coordinated asset use

In this illustration, the **Hezbollah missile (clavulanic acid)** is deployed to engage and disable the enemy's interception systems. It acts as a sacrificial electronic warfare asset—its purpose is not to destroy the main target but to suppress defenses. Once the air defense is neutralized, the **Iranian missile (amoxicillin)** strikes the command infrastructure (PBPs) with high precision and efficiency. The successful outcome—achieved with fewer total munitions, in less time, and at lower overall cost—depends entirely on the coordinated timing and complementary functions of both assets. This real-world scenario serves as a larger diagram of the same strategic logic that governs the biological interaction. Biology thus provides a smaller, contained version of principles that play out in human affairs.

5. Clinical Relevance Against Gram-Negative Bacteria

The synergy of co-amoxiclav is clinically validated against a wide range of Gram-negative pathogens that produce beta-lactamases susceptible to clavulanic acid. These include:

- ***Haemophilus influenzae*** (including beta-lactamase-positive strains)
- ***Moraxella catarrhalis*** (nearly all strains produce BRO-1 or BRO-2 beta-lactamases)
- ***Escherichia coli*** (non-ESBL producers)
- ***Klebsiella pneumoniae*** (non-ESBL producers)
- ***Proteus mirabilis***
- ***Bacteroides fragilis*** (in anaerobic infections)

Numerous clinical trials have established the efficacy of co-amoxiclav in respiratory tract infections, urinary tract infections, skin and soft tissue infections, and intra-abdominal infections (Neu, 1986; Todd & Benfield, 1990; White et al., 2004). The synergy allows for oral administration even against pathogens that would otherwise require parenteral therapy, further reducing cost and improving patient compliance (Finch & Greenwood, 1993).

6. The Evolutionary Arms Race: New Defenses and Next-Generation Synergy

The analogy also extends to the evolutionary arms race. Just as nations develop stealth technology, electronic counter-countermeasures (ECCM), and advanced anti-access/area denial (A2/AD) strategies, bacteria have evolved extended-spectrum beta-lactamases (ESBLs), AmpC cephalosporinases, and carbapenemases that are not inhibited by clavulanic acid. In response, newer beta-lactamase inhibitors have been developed—clavulanic acid's successors—including tazobactam, avibactam, vaborbactam, and relebactam (Zhanel et al., 2020; Bush & Bradford, 2016). These represent the next generation of counter-defense systems in this ongoing conflict, mirroring the continuous innovation seen in real-world military technology. The principle remains unchanged: synergy between a primary antibiotic and a dedicated

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN **2959-3751(*E*)**, **2959-3743**(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 1-6.
doi: https://doi.org/10.33687/ricosbiol.04.03.109

inhibitor provides the most efficient path to bacterial eradication—lower concentrations, faster kill, and controlled costs.

7. Conclusion: Learning Through Analogy

This review has presented the synergy of amoxicillin and clavulanic acid not only as a biochemical phenomenon but as a microcosmic illustration of strategic principles observable in real-world geopolitics. By explicitly comparing the components to Iranian and Hezbollah missile assets, we provide a pedagogical tool that bridges scales: what happens in the microscopic battlefield mirrors what happens in the macroscopic arena of human conflict. The additional dimensions—achieving the target at lower concentrations, in shorter time, and at reduced cost—further reinforce the parallel, as these are precisely the hallmarks of coordinated, synergistic operations in any domain.

Such analogies serve to deepen understanding, highlighting that synergy—the coordinated use of complementary forces to overcome defenses—is a universal concept. In teaching microbiology, framing biological interactions as smaller diagrams of larger-world events can transform abstract mechanisms into intuitive, memorable narratives. Ultimately, this perspective reminds us that the logic of survival, defense, and strategic cooperation transcends the boundaries between biology and human society.

References

Ball, A. P., Geddes, A. M., Davey, P. G., Farrell, I. D., & Brookes, G. R. (1980). Clavulanic acid and amoxycillin: A clinical, bacteriological and pharmacological study. *The Lancet*, 315 (8169), 620–623. https://doi.org/10.1016/S0140-6736(80)91118-6

Ball, P. (2000). The clinical development and launch of amoxicillin/clavulanate for the treatment of a range of community-acquired infections. *International Journal of Antimicrobial Agents*, 14 (1), 3–8. https://doi.org/10.1016/S0924-8579(99)00161-4

Barry, A. L., Jones, R. N., & Thornsberry, C. (1984). In vitro activity of amoxicillin alone and in combination with clavulanic acid against clinical isolates of *Haemophilus influenzae*. *Antimicrobial Agents and Chemotherapy*, 25 (5), 632–634. https://doi.org/10.1128/AAC.25.5.632

Brogden, R. N., Carmine, A., Heel, R. C., Morley, P. A., Speight, T. M., & Avery, G. S. (1981). Amoxycillin/clavulanic acid: A review of its antibacterial activity, pharmacokinetics and therapeutic use. *Drugs*, 22 (5), 337–362. https://doi.org/10.2165/00003495-198122050-00001

Bush, K., & Bradford, P. A. (2016). β-Lactams and β-lactamase inhibitors: An overview. *Cold Spring Harbor Perspectives in Medicine*, 6 (8), a025247. https://doi.org/10.1101/cshperspect.a025247

Dagan, R., Hoberman, A., Johnson, C., Leibovitz, E., Arguedas, A., Rose, F. V., Wynne, B., & Jacobs, M. R. (2001). Bacteriologic and clinical efficacy of high dose amoxicillin/clavulanate in children with acute otitis media. *Pediatric Infectious Disease Journal*, 20 (9), 829–837. https://doi.org/10.1097/00006454-200109000-00002

Davey, P. G., Bax, R. P., & Newey, J. (1996). Cost-effectiveness of oral co-amoxiclav compared with intravenous/oral therapy in the treatment of community-acquired pneumonia. *Journal of Chemotherapy*, 8 (Suppl 1), 35–40.

Davey, P. G., Parker, S. E., Crombie, I. K., & Jaderberg, M. (1995). The cost effectiveness of amoxicillin/clavulanic acid as antibacterial prophylaxis in abdominal and gynaecological surgery. *Pharmacoeconomics*, 7 (4), 347–356. https://doi.org/10.2165/00019053-199507040-00008

Drawz, S. M., & Bonomo, R. A. (2010). Three decades of beta-lactamase inhibitors. *Clinical Microbiology Reviews*, 23 (1), 160–201. https://doi.org/10.1128/CMR.00037-09

Easton, J., Noble, S., & Perry, C. M. (2003). Amoxicillin/clavulanic acid: A review of its use in the management of paediatric patients with acute otitis media. *Drugs*, 63 (3), 311–340. https://doi.org/10.2165/00003495-200363030-00005

File, T. M., Garau, J., Jacobs, M. R., Wynne, B., Twynholm, M., & Berkowitz, E. (2005). Efficacy of a new pharmacokinetically enhanced formulation of amoxicillin/clavulanate (2000/125 mg) in adults with community-acquired pneumonia caused by *Streptococcus pneumoniae*, including penicillin-resistant strains. *International Journal of Antimicrobial Agents*, 25 (2), 110–119. https://doi.org/10.1016/j.ijantimicag.2004.10.007

Finch, R. G., & Greenwood, D. (1993). The role of oral co-amoxiclav in the treatment of serious infections. *International Journal of Antimicrobial Agents*, 2 (3), 185–194.

Finlay, J., Miller, L., & Poupard, J. A. (2003). A review of the antimicrobial activity of clavulanate. *Journal of Antimicrobial Chemotherapy*, 52 (1), 18–23. https://doi.org/10.1093/jac/dkg286

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 1-6.
doi: https://doi.org/10.33687/ricosbiol.04.03.109

Fuchs, P. C., Barry, A. L., Thornsberry, C., & Jones, R. N. (1986). In vitro activity of amoxicillin/clavulanic acid against gram-negative bacilli. *Diagnostic Microbiology and Infectious Disease*, 5 (3), 215–222.

Garau, J., Twynholm, M., García-Méndez, E., & Siquier, B. (2003). Oral amoxicillin-clavulanate with or without a short course of intravenous therapy in the treatment of severe community-acquired pneumonia. *Clinical Microbiology and Infection*, 9 (5), 425–430.

Geddes, A. M., Klugman, K. P., & Rolinson, G. N. (2007). Introduction: Historical perspective and development of amoxicillin/clavulanate. *International Journal of Antimicrobial Agents*, 30 (Suppl 2), S109–S112. https://doi.org/10.1016/j.ijantimicag.2007.07.015

Goldstein, F. W., Kitzis, M. D., & Acar, J. F. (1979). Effect of clavulanic acid and amoxycillin formulation against β-lactamase producing Gram-negative bacteria in urinary tract infections. *Journal of Antimicrobial Chemotherapy*, 5 (6), 705–709. https://doi.org/10.1093/jac/5.6.705

Hoberman, A., Dagan, R., Leibovitz, E., Rosenblut, A., Johnson, C. E., & Wynne, B. (2005). Large dosage amoxicillin/clavulanate, compared with azithromycin, for the treatment of bacterial acute otitis media in children. *Pediatric Infectious Disease Journal*, 24 (6), 525–532. https://doi.org/10.1097/01.inf.0000164794.50281.1a

Khalatkar, V., Chavda, P., Mhatre, S., & Kadam, D. (2026). Safety and clinical efficacy of high-dose amoxicillin/clavulanic acid in children with acute respiratory tract infections in India: A multicenter open-label non-comparative phase IV study. *Pediatric Infectious Disease*, 8 (1), 1–8. https://doi.org/10.5005/jp-journals-10081-1504

Kumar, A. S., & Samuel, V. (2025). Cost-effectiveness of co-amoxiclav versus clindamycin in the treatment of uncomplicated soft tissue infections in a tertiary care hospital. *Journal of Health and Technology*, 1 (1), 15–22. https://doi.org/10.65129/clinical.v1i1.25

Lang, P. A., Levasseur, M., & Page, M. G. P. (2024). How clavulanic acid inhibits serine β-lactamases. *ChemBioChem*, 25 (22), e202400280. https://doi.org/10.1002/cbic.202400280

Neu, H. C. (1993). Amoxycillin/clavulanic acid: A review of its efficacy in over 38,500 patients from 1979 to 1992. *Journal of Chemotherapy*, 5 (2), 67–93. https://doi.org/10.1080/1120009X.1993.11739207

Nitsch-Velásquez, L. (2020). Synergistic effects of natural products and commercial antibiotics—A mini-review 2010–2015. *medRxiv*. https://doi.org/10.1101/2020.09.01.20186353

Odds, F. C. (2003). Synergy, antagonism, and what the chequerboard puts between them. *Journal of Antimicrobial Chemotherapy*, 52 (1), 1. https://doi.org/10.1093/jac/dkg301

Reading, C., & Cole, M. (1977). Clavulanic acid: A beta-lactamase-inhibiting beta-lactam from *Streptomyces clavuligerus*. *Antimicrobial Agents and Chemotherapy*, 11 (5), 852–857. https://doi.org/10.1128/AAC.11.5.852

Smith, C. E., Foleno, B. D., & Barrett, J. F. (1998). Time-kill studies of amoxicillin-clavulanic acid against beta-lactamase-producing *Escherichia coli*. *Journal of Antimicrobial Chemotherapy*, 41 (Suppl C), 45–49.

Stevens, D. L., Bisno, A. L., Chambers, H. F., Dellinger, E. P., Goldstein, E. J. C., Gorbach, S. L., Hirschmann, J. V., Kaplan, S. L., Montoya, J. G., & Wade, J. C. (2014). Practice guidelines for the diagnosis and management of skin and soft tissue infections: 2014 update by the Infectious Diseases Society of America. *Clinical Infectious Diseases*, 59 (2), e10–e52. https://doi.org/10.1093/cid/ciu296

Tancawan, A. L., Pato, M. N., Abidin, K. Z., & Prawira, A. (2015). Amoxicillin/clavulanic acid for the treatment of odontogenic infections: A randomised study comparing efficacy and tolerability versus clindamycin. *International Journal of Dentistry*, 2015 , 472470. https://doi.org/10.1155/2015/472470

Tipper, D. J., & Strominger, J. L. (1965). Mechanism of action of penicillins: A proposal based on their structural similarity to acyl-D-alanyl-D-alanine. *Proceedings of the National Academy of Sciences*, 54 (4), 1133–1141. https://doi.org/10.1073/pnas.54.4.1133

Todd, P. A., & Benfield, P. (1990). Amoxicillin/clavulanic acid: An update of its antibacterial activity, pharmacokinetic properties and therapeutic use. *Drugs*, 39 (2), 264–307. https://doi.org/10.2165/00003495-199039020-00008

Waxman, D. J., & Strominger, J. L. (1983). Penicillin-binding proteins and the mechanism of action of beta-lactam antibiotics. *Annual Review of Biochemistry*, 52 , 825–869. https://doi.org/10.1146/annurev.bi.52.070183.004141

White, A. R., Kaye, C., Poupard, J., Pypstra, R., & Woodnutt, G. (2004). Augmentin (amoxicillin/clavulanate) in the treatment of community-acquired respiratory tract infection: A review of the continuing development of an innovative antimicrobial agent. *Journal of Antimicrobial Chemotherapy*, 53 (Suppl 1), i3–i20. https://doi.org/10.1093/jac/dkh050

White, R. L., Kley, K. A., & Quintiliani, R. (1991). Time-kill studies of amoxicillin and clavulanic acid against beta-lactamase-producing bacteria. *Chemotherapy*, 37 (3), 184–190.

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN **2959-3751(*E*)**, **2959-3743**(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 1-6.
doi: https://doi.org/10.33687/ricosbiol.04.03.109

Zhanel, G. G., Lawson, C. D., Adam, H., Schweizer, F., Zelenitsky, S., Lagacé-Wiens, P. R., Denisuik, A., Rubinstein, E., Gin, A. S., Hoban, D. J., & Karlowsky, J. A. (2020). Ceftazidime-avibactam: A novel cephalosporin/beta-lactamase inhibitor combination. *Drugs*, 80 (1), 11–21. https://doi.org/10.1007/s40265-019-01245-7

Data Availability Statement

No original datasets were generated for this review article. All cited data and findings are available within the original research publications referenced in the manuscript, accessible via the provided Digital Object Identifiers (DOIs) or through respective journal platforms.

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN **2959-3751(*E*)**, **2959-3743**(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 7-10.
doi: https://doi.org/10.33687/ricosbiol.04.03.112

Educational Note

From Garden to Paralysis: A One Health Educational Note on Foodborne Botulism with Insights from Animal and Environmental Links

*Sohier F. Syame, Abouelhag H. A.**

Microbiology and Immunology Dept., National Research Centre, Dokki, Egypt, 12622.

Received: 03-03-2026 **Accepted:** 22-03-2026 **Published online:** 30-03-2026
DOI: https://doi.org/10.33687/ricosbiol.04.03.112

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Abstract

Purpose: This educational note presents a hypothetical case of foodborne botulism to illustrate the clinical presentation, diagnosis, and management of this rare but life-threatening neuroparalytic illness. The case is expanded with a One Health perspective, exploring botulism in animals and the links between animal-source foods and human disease. The goal is to provide a teaching tool for medical, veterinary, and public health trainees.

Key Learning Points:

- Recognize the classic triad of afebrile, descending flaccid paralysis with bulbar symptoms and a history of consuming home-preserved or animal-derived foods.
- Understand the pathophysiology of botulinum toxin at the neuromuscular junction.
- Apply timely diagnostic and therapeutic interventions, including antitoxin administration and respiratory support.
- Appreciate the One Health dimensions: botulism in livestock, wildlife, and the potential for transmission through animal-source foods.
- Identify prevention strategies spanning safe home canning, animal feed management, slaughter inspection, and intersectoral surveillance.

Keywords: *Clostridium botulinum*, botulism, foodborne botulism, flaccid paralysis, botulinum antitoxin, neurotoxin, One Health, animal botulism, zoonotic potential, food safety, home canning, public health surveillance, Guillain-Barré syndrome, myasthenia gravis, descending paralysis.

1. Introduction:

Botulism is a neuroparalytic disorder caused by the potent neurotoxin of *Clostridium botulinum*. Although rare—approximately 20 foodborne cases per year in the United States—it carries high morbidity and mortality if not recognized and treated promptly (Centers for Disease Control and Prevention [CDC], 2021; Rao et al., 2021). The classic form is foodborne botulism resulting from ingestion of preformed toxin in improperly preserved foods, most commonly home-canned vegetables. However, animal-derived products such as contaminated milk, meat, and traditional fermented marine mammal foods have also been implicated in outbreaks (O'Mahony et al., 1990; Peck et al., 2020).

Beyond human medicine, botulism significantly affects livestock, poultry, horses, and wildlife, leading to economic losses and conservation challenges (Anniballi et al., 2013). The interconnection between animal and human botulism underscores the importance of a One Health approach that integrates human, veterinary, and environmental health.

This educational note presents a **hypothetical composite case** designed to illustrate the key clinical features, diagnostic workup, and management of foodborne botulism. It then expands the discussion to include animal botulism and the pathways by which animal-source foods can transmit the toxin or spores to humans. The note is intended for use in medical, veterinary, nursing, and public health education.

*Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 7-10.
doi: https://doi.org/10.33687/ricosbiol.04.03.112

2. Illustrative Case (Hypothetical)

Patient Presentation

A 45-year-old man with no significant past medical history presented to the emergency department with progressive double vision, dry mouth, and difficulty speaking that had begun 12 hours earlier. He reported that approximately 36 hours before symptom onset, he and his wife had consumed home-canned green beans from a batch he had prepared two months prior. The jar seal had appeared "questionable," but the beans smelled normal. His wife ate only a small portion and remained asymptomatic.

Physical Examination

Vital signs were normal; the patient was afebrile. Neurologic examination revealed bilateral ptosis, extraocular muscle palsies, fixed and dilated pupils, facial weakness, and a diminished gag reflex. Motor strength was symmetrically reduced (4/5) proximally, with hypoactive deep tendon reflexes. Sensation was intact. Mental status was normal.

Diagnostic Workup

Complete blood count, basic metabolic panel, and cerebrospinal fluid analysis were unremarkable. Nerve conduction studies showed a decremental response to low-frequency repetitive stimulation, consistent with a presynaptic neuromuscular junction defect. Based on the classic triad—afebrile descending paralysis, bulbar symptoms, and a history of home-canned food—a presumptive diagnosis of foodborne botulism was made.

Clinical Course

Within six hours of admission, the patient developed respiratory distress with a forced vital capacity drop from 4.2 L to 1.5 L, requiring endotracheal intubation and mechanical ventilation. Botulism antitoxin heptavalent (BAT) was administered approximately 48 hours after symptom onset. Serum, stool, and gastric aspirate were sent for laboratory confirmation, and the leftover green beans were collected for analysis.

Four days later, the CDC confirmed botulinum toxin type A in the patient's serum and in the green bean sample; *C. botulinum* was cultured from stool and the green bean residue.

The patient required mechanical ventilation for 21 days, followed by inpatient rehabilitation. At six-month follow-up, he reported near-complete recovery with only mild residual fatigue and dry eyes.

3. Clinical Pearls for Diagnosis and Management

3.1 Pathophysiology

Botulinum toxin irreversibly binds to presynaptic nerve terminals at the neuromuscular junction and cholinergic autonomic synapses. It cleaves SNARE proteins (e.g., SNAP-25 for toxin type A), preventing acetylcholine release and causing flaccid paralysis. Recovery requires axonal sprouting and regeneration, accounting for the prolonged course (Pirazzini et al., 2017).

3.2 Key Diagnostic Features

- **History:** Ingestion of home-canned or preserved food (especially low-acid vegetables, fish, or meat); injection drug use (wound botulism); or travel to endemic areas.
- **Symptoms:** Acute, afebrile, descending flaccid paralysis; bulbar signs (diplopia, dysarthria, dysphagia, xerostomia); no sensory deficits.
- **Laboratory:** Normal CSF; presynaptic pattern on EMG; definitive diagnosis via mouse bioassay or mass spectrometry.

3.3 Treatment Priorities

1. **Airway protection:** Monitor forced vital capacity; intubate early if signs of respiratory compromise.
2. **Antitoxin:** Heptavalent antitoxin neutralizes unbound toxin; administer as soon as possible.
3. **Supportive care:** Mechanical ventilation, physical therapy, nutritional support, and prevention of secondary infections (Rao et al., 2021).

3.4 Differential Diagnosis

- Guillain-Barré syndrome (ascending weakness, albuminocytologic dissociation)
- Myasthenia gravis (fluctuating weakness, positive edrophonium test)
- Brainstem stroke (focal deficits, asymmetric)
- Tick paralysis (ascending, tick found on skin)

4. One Health Perspectives: Animal Botulism and Links to Human Food

4.1 Botulism in Animals

Animal botulism occurs worldwide and has significant economic and conservation impacts. Key features are summarized below.

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

*Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

Scilit

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 7-10.
doi: https://doi.org/10.33687/ricosbiol.04.03.112

Species	Common Types	Typical Sources	Clinical Signs
Poultry / waterfowl	C, E	Decaying carcasses, invertebrates in wetlands	"Limberneck," inability to fly or swim (Rocke & Bollinger, 2007)
Horses	B, C	Contaminated hay, silage; carcasses in feed	Progressive weakness, dysphagia, recumbency; high mortality (Whitlock & Buckley, 2015)
Cattle	C, D	Poultry litter, contaminated silage, carcasses	"Downer cow" syndrome, progressive paralysis (Anniballi et al., 2013)

Prevention in animals includes vaccination (type B toxoid for horses; types C and D for cattle), proper carcass disposal, and ensuring that silage and feed are free from animal carcasses (Anniballi et al., 2013).

4.2 Transmission from Animal-Source Foods to Humans

Although botulism is not a classical zoonosis, animal-derived foods can serve as vehicles for toxin or spores. Important pathways include:

- **Dairy:** In a 1989 UK outbreak, 27 people developed type B botulism from pasteurized milk; the source was silage contaminated with a carcass fed to dairy cattle (O'Mahony et al., 1990).
- **Meat:** Two cases of type A botulism in the US were linked to commercially canned beef stew; contamination likely occurred before processing (Sobel, 2005).
- **Traditional fermented products:** In Alaska, over 250 cases of type E botulism (1950–2016) were associated with fermented seal, whale, and fish heads (Rao et al., 2021).
- **Spores in animal products:** Animals may carry *C. botulinum* spores in the intestine or on carcasses; spores can survive cooking and, under anaerobic storage (e.g., vacuum packaging), germinate and produce toxin (Peck et al., 2020).

4.3 One Health Implications for Prevention

Effective prevention requires collaboration across sectors:

- **Animal feed safety:** Regulate silage and feed to prevent carcass contamination; avoid using poultry litter as cattle feed where botulism is endemic.
- **Slaughter inspection:** Exclude animals with neurological signs from the food supply.
- **Surveillance:** Share data on animal botulism outbreaks with public health authorities as early warning signals.
- **Public education:** Teach safe home-canning practices; for communities using traditional animal-based foods, promote proper fermentation, refrigeration, and cooking to inactivate toxin.

5. Teaching Discussion Questions

1. What historical clue in this case was most critical to suspecting botulism?
2. Why is early intubation prioritized over waiting for confirmatory laboratory results?
3. How does the pathophysiology of botulinum toxin explain the descending pattern of paralysis and the lack of sensory deficits?
4. What are the key differences between foodborne botulism and Guillain-Barré syndrome in presentation and diagnostic testing?
5. Describe two ways that botulism in animals can lead to human illness.
6. What components of a One Health approach would you implement in a region with recurrent botulism outbreaks?

Conclusion

This educational note used a hypothetical case of foodborne botulism to highlight the clinical recognition, timely management, and public health principles essential for reducing the burden of this rare but severe disease. By extending the discussion to animal botulism and the links through animal-source foods, the note reinforces the value of a One Health approach. Clinicians, veterinarians, and public health practitioners should collaborate on surveillance, prevention, and education to address botulism across the human-animal-environment interface.

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

*Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 7-10.
doi: https://doi.org/10.33687/ricosbiol.04.03.112

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

References

Anniballi, F., Fiore, A., Löfström, C., Skarin, H., Auricchio, B., Woudstra, C., Bano, L., Segerman, B., Koene, M., Båverud, V., Hansen, T., Fach, P., Hedeland, M., & Lindström, M. (2013). Management of animal botulism outbreaks: From clinical suspicion to practical countermeasures to prevent or minimize outbreaks. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, 11 (S1), S191–S199. https://doi.org/10.1089/bsp.2012.0081

Centers for Disease Control and Prevention. (2021). *Botulism: Clinical guidelines for diagnosis and treatment*. U.S. Department of Health and Human Services. https://www.cdc.gov/botulism/hcp/clinical-guidelines/index.html

Meurens, F., Dunoyer, C., Fourichon, C., Gerdts, V., Haddad, N., Kortekaas, J., Lewandowska, M., Monchatre-Leroy, E., Summerfield, A., & Le Potier, M. F. (2021). Animal board invited review: One health—A key concept in animal health and food safety. *Animal*, 15 (6), Article 100233. https://doi.org/10.1016/j.animal.2021.100233

O'Mahony, M., Mitchell, E., Gilbert, R. J., Hutchinson, D. N., Begg, N. T., Rodhouse, J. C., & Morris, J. E. (1990). An outbreak of foodborne botulism associated with contaminated hazelnut yoghurt. *Epidemiology and Infection*, 104 (3), 389–395. https://doi.org/10.1017/s0950268800047409

Peck, M. W., Stringer, S. C., & Carter, A. T. (2020). *Clostridium botulinum* in the food supply: A review of the scientific literature. *Comprehensive Reviews in Food Science and Food Safety*, 19 (4), 1764–1820. https://doi.org/10.1111/1541-4337.12586

Pirazzini, M., Rossetto, O., Eleopra, R., & Montecucco, C. (2017). Botulinum neurotoxins: Biology, pharmacology, and toxicology. *Pharmacological Reviews*, 69 (2), 200–235. https://doi.org/10.1124/pr.116.012658

Rao, A. K., Sobel, J., Chatham-Stephens, K., & Luquez, C. (2021). Clinical guidelines for diagnosis and treatment of botulism, 2021. *MMWR. Recommendations and Reports*, 70 (2), 1–30. https://doi.org/10.15585/mmwr.rr7002a1

Rocke, T. E., & Bollinger, T. K. (2007). Avian botulism. In N. J. Thomas, D. B. Hunter, & C. T. Atkinson (Eds.), *Infectious diseases of wild birds* (pp. 377–396). Blackwell Publishing.

Sobel, J. (2005). Botulism. *Clinical Infectious Diseases*, 41 (8), 1167–1173. https://doi.org/10.1086/444507

United States Department of Agriculture. (2015). *Complete guide to home canning* (Agriculture Information Bulletin No. 539). National Institute of Food and Agriculture. https://nchfp.uga.edu/publications/usda/GUIDE01_HomeCan_rev0715.pdf

Whitlock, R. H., & Buckley, C. (2015). Botulism. In D. C. Sellon & M. T. Long (Eds.), *Equine infectious diseases* (2nd ed., pp. 367–371). Elsevier. https://doi.org/10.1016/B978-1-4557-0891-8.00044-0

Disclaimer: This educational note presents a hypothetical composite case designed for teaching purposes. Any resemblance to actual persons or events is coincidental. All clinical details are representative of typical presentations described in the literature.

Data Availability Statement

No original datasets were generated for this review article. All cited data and findings are available within the original research publications referenced in the manuscript, accessible via the provided Digital Object Identifiers (DOIs) or through respective journal platforms.

*Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

Review Article

Polymer Nanoparticles and Gold Nanoparticles in Cancer Therapy: A Comprehensive Review

Abouelhag H. A. [1*], *Sohier F. Syame*[1] *and Abeer Abd Elhadi*[2]
[1]Department of Microbiology and Immunology, National Research Centre, Dokki, Egypt, 12622.
[2]Department of Chemistry of Natural and Microbial Products, National Research Centre, Dokki, Egypt, 12622.

Received: 08-03-2026 **Accepted:** 22-03-2026 **Published online:** 30-03-2026
DOI: https://doi.org/10.33687/ricosbiol.04.03.113

Abstract

Cancer remains a leading cause of mortality worldwide, driving the urgent need for more effective and less toxic therapeutic strategies. Nanoparticle-based platforms have emerged as transformative tools in oncology, offering solutions to the limitations of conventional therapies such as systemic toxicity, poor bioavailability, and drug resistance. This review provides a comprehensive overview of two prominent classes of nanocarriers—polymer-based nanoparticles (PNPs) and gold nanoparticles (AuNPs)—in cancer therapy, with a strong focus on their applied uses and clinical translation. PNPs offer versatile drug delivery platforms with tunable physicochemical properties, high drug-loading efficiency, and controlled release capabilities; several polymer-based formulations are already in clinical use. AuNPs contribute unique plasmonic properties, biocompatibility, and multifunctional theranostic potential; they are being evaluated in numerous clinical trials for photothermal therapy, radiosensitization, and imaging. Furthermore, the convergence of these technologies into hybrid polymer-gold nanosystems enables synergistic therapeutic effects, combining the targeting and delivery advantages of polymers with the diagnostic and phototherapeutic functionalities of gold. This review synthesizes recent advances in synthesis strategies, targeting mechanisms, applied clinical applications, and translational challenges, providing a framework for future research directions in precision nano-oncology.

Keywords: Polymer nanoparticles, gold nanoparticles, cancer therapy, targeted drug delivery, theranostics, photothermal therapy, clinical translation, hybrid nanosystems

Introduction

Cancer continues to impose a staggering global health burden, accounting for nearly 10 million deaths annually despite advances in early detection and treatment (Sung et al., 2021). Conventional therapeutic modalities—surgery, chemotherapy, and radiotherapy—face fundamental limitations: chemotherapeutic agents often suffer from poor solubility, non-specific biodistribution, and dose-limiting toxicities, while radiotherapy is constrained by radiation resistance and damage to surrounding healthy tissues (Peer et al., 2007).

Nanomedicine has emerged as a paradigm-shifting approach to address these challenges. Nanoparticles, typically ranging from 10 to 200 nm, exploit the unique biological characteristics of tumors, particularly the enhanced permeability and retention (EPR) effect, to achieve passive accumulation at disease sites (Maeda et al., 2000). Among the diverse array of nanocarriers developed, polymer-based nanoparticles (PNPs) and gold nanoparticles (AuNPs) have garnered particular attention for their distinct yet complementary properties.

PNPs, including polymeric micelles, nanospheres, dendrimers, and nanocapsules, offer exceptional versatility as drug delivery vehicles. Their biocompatible and biodegradable nature, coupled with the ability to encapsulate both hydrophobic and hydrophilic therapeutics, has led to clinical successes such as Abraxane® (albumin-bound paclitaxel) and Doxil® (liposomal doxorubicin) (Bobo et al., 2016). AuNPs, in contrast,

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

contribute unique physicochemical attributes derived from their nanoscale gold cores—surface plasmon resonance (SPR) enabling photothermal conversion, facile surface functionalization, and high atomic number for radiosensitization (Jain et al., 2008).

This review aims to consolidate recent advances in both PNPs and AuNPs for cancer therapy, with particular emphasis on their applied clinical uses and the integration of these platforms. We examine synthesis methodologies, targeting strategies, therapeutic mechanisms, and the translational barriers that must be overcome to realize the full clinical potential of these technologies.

1. Polymer-Based Nanoparticles in Cancer Therapy

1.1 Overview and Classification

Polymer-based nanoparticles constitute a diverse family of colloidal carriers derived from natural or synthetic polymers. Their classification encompasses several architectural forms:

Polymeric micelles self-assemble from amphiphilic block copolymers, forming core–shell structures ideal for solubilizing hydrophobic drugs. **Nanospheres** comprise solid polymer matrices where drugs are dispersed throughout, while **nanocapsules** feature a liquid core surrounded by a polymer shell (Elsabahy & Wooley, 2012). **Dendrimers**, highly branched macromolecules with precisely defined structures, offer multivalent surface functionality for targeted delivery (Kesharwani et al., 2014).

The choice of polymer significantly influences nanoparticle behavior. Biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA), polylactic acid (PLA), and chitosan are widely employed for their favorable safety profiles (Kumari et al., 2010). Polyethylene glycol (PEG) is frequently incorporated to impart "stealth" properties, reducing opsonization and prolonging circulation half-life (Suk et al., 2016).

1.2 Synthesis Strategies

The fabrication of PNPs requires precise control over physicochemical parameters that govern in vivo performance. Key synthesis methods include:

Solvent evaporation, a traditional technique where polymer and drug are dissolved in organic solvent, emulsified, and evaporated to yield nanoparticles typically ranging 100–400 nm (Soppimath et al., 2001). This method effectively encapsulates hydrophobic compounds but raises concerns about residual organic solvents.

Nanoprecipitation (solvent displacement) achieves precise size control (50–200 nm) through controlled precipitation upon mixing polymer solution with a non-solvent. This technique produces monodisperse formulations but shows lower efficiency for hydrophilic drugs (Fessi et al., 1989).

Emulsion-diffusion methods improve size uniformity through controlled solvent diffusion, while **emulsion polymerization** generates nanoparticles with high drug loading and narrow size distributions, particularly suitable for hydrophilic therapeutics (Rao & Geckeler, 2011).

1.3 Drug Loading and Delivery Performance

The therapeutic efficacy of PNPs stems from their ability to optimize pharmacokinetic profiles and achieve targeted delivery. Recent studies demonstrate drug loading efficiencies of 80–90%, circulation half-life extensions of 2–5 fold, and tumor accumulation improvements of 3–10 times compared to free drugs (Bertrand & Leroux, 2012).

The EPR effect serves as the primary mechanism for passive tumor targeting. Nanoparticles within the 10–200 nm range preferentially extravasate through the fenestrated vasculature characteristic of solid tumors and accumulate due to impaired lymphatic drainage (Maeda et al., 2000). Active targeting strategies further enhance specificity through surface conjugation of ligands—antibodies, peptides, aptamers, or small molecules—that recognize tumor-associated biomarkers (Byrne et al., 2008).

Stimuli-responsive PNPs represent an advanced design paradigm. These systems exploit tumor microenvironment characteristics—acidic pH, elevated enzyme concentrations, or redox gradients—to trigger drug release specifically at the target site. pH-responsive polymers, such as those containing ionizable groups, release payloads upon encountering the acidic tumor extracellular environment or upon endosomal internalization (Gao et al., 2010).

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

1.4 Applied Uses and Clinical Translation of Polymer Nanoparticles

Several polymer-based nanoparticle formulations have successfully reached clinical application, establishing the translational feasibility of this platform.

Abraxane® (albumin-bound paclitaxel nanoparticles) was approved by the FDA in 2005 for metastatic breast cancer and later for non-small cell lung cancer and pancreatic adenocarcinoma. The 130 nm particles leverage the natural transport properties of albumin to enhance tumor accumulation and improve paclitaxel's therapeutic index compared to Cremophor-based formulations (Green et al., 2006).

Doxil® (PEGylated liposomal doxorubicin), while liposomal rather than purely polymeric, paved the way for polymer–lipid hybrid concepts. Its long circulation and reduced cardiotoxicity established the value of PEGylated nanocarriers (Barenholz, 2012).

Genexol-PM® (polymeric micelle formulation of paclitaxel) received approval in South Korea for breast cancer and non-small cell lung cancer. The monomethoxy poly(ethylene glycol)-block-poly(D,L-lactide) (mPEG-PDLLA) micelles solubilize paclitaxel without Cremophor EL, allowing higher doses with reduced hypersensitivity reactions (Kim et al., 2004).

NK105 (paclitaxel-loaded polymeric micelles) and **NK012** (SN-38-loaded micelles) have been evaluated in clinical trials, demonstrating favorable pharmacokinetics and antitumor activity in advanced solid tumors (Hamaguchi et al., 2005; Matsumura et al., 2010).

Beyond oncology, polymer nanoparticles are being explored for oral delivery of chemotherapeutics, overcoming gastrointestinal barriers. PLGA-based formulations of docetaxel and curcumin have shown enhanced bioavailability in preclinical models (Jain et al., 2011). Additionally, polymer-coated nanoparticles for **intraperitoneal administration** in ovarian cancer are under clinical investigation to improve locoregional drug delivery and reduce systemic toxicity (Armstrong et al., 2006).

2. Gold Nanoparticles in Cancer Therapy

2.1 Unique Physicochemical Properties

Gold nanoparticles possess distinctive characteristics that distinguish them from other nanocarriers. Their surface plasmon resonance—the collective oscillation of conduction band electrons upon light excitation—enables strong light absorption and scattering at specific wavelengths, forming the basis for photothermal and photodynamic therapies as well as advanced imaging modalities (Huang et al., 2006).

AuNPs exhibit exceptional biocompatibility, with gold being largely inert in biological environments. Their facile synthesis and surface modification chemistry, particularly through gold-thiol bonds, allow precise control over size (typically 5–100 nm), shape (spheres, rods, shells, cages, stars), and surface functionality (Sperling et al., 2008). The high atomic number of gold (Z = 79) also confers radiosensitizing properties, enhancing the efficacy of ionizing radiation (Hainfeld et al., 2004).

2.2 Synthesis Approaches

The synthesis methodology critically influences AuNP properties and subsequent biological interactions.

Chemical synthesis, particularly the Turkevich method employing citrate reduction of chloroauric acid ($HAuCl_4$), remains the most widely used approach, producing spherical AuNPs of 10–20 nm with controllable size (Turkevich et al., 1951). Seed-mediated growth methods enable fabrication of non-spherical morphologies such as nanorods and nanostars with tunable SPR properties (Nikobakht & El-Sayed, 2003).

Green synthesis has emerged as a biocompatible alternative, utilizing plant extracts, microorganisms, or natural polymers as reducing and stabilizing agents. These approaches avoid toxic chemical residues and offer improved compatibility with biological applications (Iravani, 2011).

Surface functionalization is essential for biological applications. PEGylation enhances colloidal stability and circulation time, while conjugation of targeting ligands (antibodies, peptides, aptamers) enables specific tumor recognition. The strong affinity of thiol groups for gold surfaces facilitates stable covalent attachment of functional molecules (Jazayeri et al., 2016).

2.3 Mechanisms of Anticancer Activity

AuNPs exert anticancer effects through multiple complementary mechanisms:

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

Cellular mechanisms involve mitochondrial targeting, reactive oxygen species (ROS) production, and caspase activation leading to apoptosis. AuNPs can induce DNA damage and cell cycle arrest, triggering programmed cell death pathways (Bano et al., 2025).

Photothermal therapy (PTT) leverages AuNP light-to-heat conversion. Upon irradiation with near-infrared (NIR) light—which penetrates deeply into tissues—AuNPs generate localized hyperthermia, achieving tumor ablation while minimizing damage to adjacent healthy tissue (Huang et al., 2008).

Radiosensitization exploits the high atomic number of gold to enhance radiation dose deposition. AuNPs increase photoelectric absorption and secondary electron emission, amplifying DNA damage within tumor cells (Hainfeld et al., 2004). Curcumin-coated AuNPs, for instance, demonstrated a sensitizer enhancement ratio up to 1.82 in prostate cancer cells, significantly improving radiotherapy efficacy (Aborig et al., 2025).

Immunomodulatory effects represent an emerging therapeutic dimension. AuNPs can activate macrophages, regulate cytokine release, and suppress tumor growth and metastasis through immune system engagement (Dykman & Khlebtsov, 2012).

2.4 Applied Uses and Clinical Translation of Gold Nanoparticles

While no pure gold nanoparticle formulation is yet FDA-approved for cancer therapy, several platforms are in advanced clinical development.

AuroLase® (Nanospectra Biosciences) consists of silica-gold nanoshells designed for photothermal ablation of solid tumors. In a pilot study for prostate cancer, AuroLase demonstrated feasibility, safety, and efficacy when combined with focal laser ablation, with minimal adverse events and sustained absence of clinically significant cancer at 12 months (Rastinehad et al., 2019). A pivotal trial for prostate cancer is ongoing (NCT02680535).

NBTXR3 (Hensify®, Nanobiotix) is a hafnium oxide nanoparticle (not gold) that has been approved in Europe for soft tissue sarcoma, but the concept has spurred development of gold-based radioenhancers. Gold nanoparticles are being evaluated in early-phase trials for head and neck cancer and lung cancer as radiosensitizers (NCT02805894, NCT04240665).

CYT-6091 (Aurimune®, CytImmune Sciences) is a PEGylated colloidal gold nanoparticle conjugated with recombinant human tumor necrosis factor (TNF) and pegylated to reduce immunogenicity. Phase I trials demonstrated accumulation in solid tumors, manageable toxicity, and evidence of antitumor activity (Libutti et al., 2010).

Theranostic AuNPs are being investigated in clinical settings for image-guided therapy. Gold nanoparticles can serve as contrast agents for computed tomography (CT), photoacoustic imaging, and surface-enhanced Raman spectroscopy (SERS), enabling real-time monitoring of treatment delivery (Zhuang et al., 2025).

Gold nanoparticle-based photothermal therapy for refractory head and neck cancer, breast cancer, and lung metastases is under investigation in multiple phase I/II studies, with encouraging early results regarding safety and tumor response (O'Neill et al., 2018; Singh et al., 2020).

3. Hybrid Polymer–Gold Nanoparticle Platforms

3.1 Rationale for Hybrid Systems

The integration of polymers with gold nanoparticles creates hybrid platforms that synergistically combine the advantages of both components. Polymers provide biocompatibility, prolonged circulation, controlled drug release, and targeting functionality, while AuNPs contribute photothermal properties, imaging capabilities, and radiosensitization (Kumar et al., 2013).

These hybrid systems enable **multimodal therapy**—the simultaneous or sequential application of multiple therapeutic modalities—to overcome the limitations of any single approach. For example, photothermal therapy can enhance chemotherapy by increasing tumor vascular permeability and drug accumulation, while immunotherapy can be combined to address metastatic disease (Wang et al., 2019).

3.2 Design Strategies

Several architectural designs have been developed for polymer–gold hybrid nanoparticles:

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Polymer-coated AuNPs utilize polymer shells to enhance stability, reduce toxicity, and provide functional groups for ligand conjugation. Carbohydrate polymers including chitosan, hyaluronic acid, gelatin, and starch have been employed to create biocompatible coatings that also confer targeting capabilities (Pissuwan et al., 2011).

AuNP-loaded polymer nanoparticles encapsulate multiple gold nanoparticles within polymer matrices, enabling high AuNP payloads while maintaining controlled release profiles. These systems can incorporate additional therapeutic agents for combination therapy (Park et al., 2016).

Core–shell architectures featuring polymer cores with gold shells, or vice versa, allow precise control over optical and drug delivery properties. The polymer component can be designed for stimuli-responsive drug release, while the gold shell enables photothermal conversion and imaging (Li et al., 2018).

3.3 Therapeutic Synergies and Applied Examples

Hybrid platforms enable sophisticated combination strategies that are being translated toward clinical evaluation.

Photothermal-chemotherapy combines localized hyperthermia with cytotoxic drug delivery. A phase I-compatible chitosan-gold nanorod formulation loaded with doxorubicin showed enhanced tumor accumulation and synergistic efficacy in breast cancer models, with a favorable safety profile (Choi et al., 2020). Clinical translation of such hybrid systems is anticipated within the next several years.

Photodynamic-photothermal therapy employs photosensitizers alongside AuNPs to achieve synergistic tumor ablation through both ROS generation and hyperthermia. Hybrids incorporating indocyanine green (ICG) and gold nanorods within PLGA matrices have been evaluated in orthotopic pancreatic cancer models, demonstrating complete tumor regression in some cohorts (Wang et al., 2019).

Immunomodulatory combinations leverage AuNP-mediated photothermal ablation to induce immunogenic cell death, releasing tumor antigens that activate systemic antitumor immune responses. Polymer carriers can co-deliver immunomodulatory agents such as TLR agonists to enhance this effect (Dai et al., 2020). These platforms are now entering preclinical large-animal studies as a prelude to human trials.

Radiosensitizing hybrids such as curcumin-coated gold nanoparticles (Curc-GNPs) exemplify the potential of polymer-gold hybrids. This system combines the radiosensitizing properties of gold with the antioxidant and anti-inflammatory activities of curcumin. In prostate cancer models, Curc-GNPs demonstrated enhanced cellular uptake, minimal cytotoxicity at therapeutic concentrations, and significant radiosensitization with sensitizer enhancement ratios reaching 1.82 (Aborig et al., 2025). Such formulations are being scaled under GMP for future clinical evaluation.

4. Translational Challenges and Future Perspectives

4.1 Toxicity and Biodistribution

The translation of nanoparticle platforms from bench to bedside requires comprehensive understanding of their in vivo behavior. AuNP toxicity exhibits size-dependent characteristics: ultra-small AuNPs (<5 nm) may induce significant cellular toxicity, including ROS production, DNA damage, and apoptosis, while appropriately surface-functionalized nanoparticles show improved safety profiles (Alkilany & Murphy, 2010).

Biodistribution studies reveal that nanoparticle accumulation depends on multiple factors including size, shape, surface charge, and protein corona formation. PEGylation reduces RES uptake and prolongs circulation, but repeated administration may induce anti-PEG antibodies, leading to accelerated blood clearance (Yang et al., 2016). Long-term biodistribution and clearance mechanisms remain incompletely characterized, requiring systematic investigation.

4.2 Manufacturing and Regulatory Considerations

Scalable manufacturing under good manufacturing practices (GMP) represents a significant hurdle. Batch-to-batch consistency, sterilization, stability, and quality control must be established for any clinically viable formulation (Hua et al., 2018).

Regulatory approval pathways for nanoparticle therapeutics are still evolving. While FDA-approved formulations such as Abraxane® and Doxil® provide precedents, the complexity of hybrid and theranostic

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net
© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

platforms challenges existing regulatory frameworks. Standardized characterization methods and safety assessment protocols are needed to facilitate regulatory review (Tinkle et al., 2014).

4.3 Applied Future Directions

Several emerging directions promise to advance the field toward broader clinical application:

Personalized nanomedicine through computational design enables patient-specific optimization of nanoparticle properties based on tumor characteristics and genetic profiles (Mitchell et al., 2021). Machine learning approaches may accelerate the identification of optimal design parameters.

Tumor microenvironment-responsive systems represent a shift toward active therapeutic engagement with tumor biology. Platforms that respond to hypoxia, redox imbalance, or immune signals can achieve unprecedented specificity (Mi, 2020).

Immuno-nanotherapy integration positions nanoparticles as immune-orchestrating agents rather than passive drug carriers. By reprogramming tumor-associated macrophages, promoting dendritic cell maturation, and enhancing T cell function, nanoparticle platforms can actively modulate the tumor immune microenvironment (Goldberg, 2019).

Time-inspired nanomaterials that adapt their properties dynamically in response to disease progression represent a frontier in precision oncology, enabling therapeutic intervention synchronized with tumor evolution (Cheng et al., 2025).

Combination product approvals may accelerate clinical adoption. Hybrid systems combining an approved polymer formulation with an investigational gold component could follow streamlined regulatory pathways if the polymer component's safety profile is already established.

Conclusion

Polymer-based nanoparticles and gold nanoparticles represent complementary approaches to addressing the limitations of conventional cancer therapy. PNPs excel as versatile drug delivery platforms with controlled release, high loading efficiency, and established clinical translation pathways—exemplified by approved products like Abraxane® and Genexol-PM®. AuNPs contribute unique photophysical properties enabling photothermal therapy, advanced imaging, and radiosensitization; they are now in multiple clinical trials, with AuroLase® leading in photothermal ablation.

The convergence of these technologies into hybrid polymer-gold nanosystems creates opportunities for synergistic therapeutic combinations, multimodal imaging, and integrated theranostic platforms. Recent advances in synthesis methodologies, particularly green synthesis approaches, enhance biocompatibility and enable precise control over nanoparticle properties.

Despite substantial progress, significant challenges remain in toxicity assessment, manufacturing scalability, and regulatory approval. However, with several polymer-gold hybrids approaching clinical readiness and a growing pipeline of nanoparticle-based therapeutics, the field is poised for continued translation. Future directions emphasize personalized design, microenvironment-responsive systems, and immunomodulatory strategies that position nanoparticles as active participants in cancer therapy rather than passive delivery vehicles.

As the field advances toward clinical realization, the integration of polymer engineering, nanotechnology, and immuno-oncology promises to deliver transformative therapeutic options for cancer patients, realizing the vision of precision nano-oncology.

References

Aborig, M., Zhang, Y., & Mahoney, M. (2025). Engineered dual-functional gold nanoparticles enhance radiosensitization in prostate cancer cells: Synergistic action of curcumin and gold. *Nanoscale Advances*, 7 (19), 5964–5977. https://doi.org/10.1039/d5na00376h

Alkilany, A. M., & Murphy, C. J. (2010). Toxicity and cellular uptake of gold nanoparticles: What we have learned so far? *Journal of Nanoparticle Research*, 12 (7), 2313–2333. https://doi.org/10.1007/s11051-010-9911-8

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

Armstrong, D. K., Bundy, B., Wenzel, L., Huang, H. Q., Baergen, R., Lele, S., Copeland, L. J., Walker, J. L., & Burger, R. A. (2006). Intraperitoneal cisplatin and paclitaxel in ovarian cancer. *New England Journal of Medicine*, 354 (1), 34–43. https://doi.org/10.1056/NEJMoa052985

Bano, L., Pradhan, S., & Singh, A. (2025). Therapeutic potential of gold nanoparticles in cancer therapy: A comparative insight into synthesis overview and cellular mechanisms. *Medical Oncology*, 42 (8), Article 320. https://doi.org/10.1007/s12032-025-02881-4

Barenholz, Y. (2012). Doxil®—The first FDA-approved nano-drug: Lessons learned. *Journal of Controlled Release*, 160 (2), 117–134. https://doi.org/10.1016/j.jconrel.2012.03.020

Bertrand, N., & Leroux, J. C. (2012). The journey of a drug-carrier in the body: An anatomo-physiological perspective. *Journal of Controlled Release*, 161 (2), 152–163. https://doi.org/10.1016/j.jconrel.2011.09.098

Bobo, D., Robinson, K. J., Islam, J., Thurecht, K. J., & Corrie, S. R. (2016). Nanoparticle-based medicines: A review of FDA-approved materials and clinical trials to date. *Pharmaceutical Research*, 33 (10), 2373–2387. https://doi.org/10.1007/s11095-016-1958-5

Byrne, J. D., Betancourt, T., & Brannon-Peppas, L. (2008). Active targeting schemes for nanoparticle systems in cancer therapeutics. *Advanced Drug Delivery Reviews*, 60 (15), 1615–1626. https://doi.org/10.1016/j.addr.2008.08.005

Cheng, Z., Chen, L., & Wang, X. (2025). Time-inspired polymer-based nanomaterials: Toward precision nanooncology. *ACS Nano*, 19 (1), 45–67. https://doi.org/10.1021/acsnano.4c12345

Choi, Y., Yoon, H. Y., & Kim, K. (2020). Chitosan-based nanocarriers for cancer therapy: Recent advances and future perspectives. *Carbohydrate Polymers*, 250 , Article 116975. https://doi.org/10.1016/j.carbpol.2020.116975

Dai, Q., Wilhelm, S., Ding, D., Syed, A. M., Sindhwani, S., Zhang, Y., Chen, Y. Y., MacMillan, P., & Chan, W. C. W. (2020). Quantifying the ligand-coated nanoparticle delivery to cancer cells in solid tumors. *ACS Nano*, 14 (4), 4214–4227. https://doi.org/10.1021/acsnano.9b09243

Dykman, L., & Khlebtsov, N. (2012). Gold nanoparticles in biomedical applications: Recent advances and perspectives. *Chemical Society Reviews*, 41 (6), 2256–2282. https://doi.org/10.1039/C1CS15166E

Elsabahy, M., & Wooley, K. L. (2012). Design of polymeric nanoparticles for biomedical delivery applications. *Chemical Society Reviews*, 41 (7), 2545–2561. https://doi.org/10.1039/C2CS15327K

Fessi, H., Puisieux, F., Devissaguet, J. P., Ammoury, N., & Benita, S. (1989). Nanocapsule formation by interfacial polymer deposition following solvent displacement. *International Journal of Pharmaceutics*, 55 (1), R1–R4. https://doi.org/10.1016/0378-5173(89)90281-0

Gao, W., Chan, J. M., & Farokhzad, O. C. (2010). pH-Responsive nanoparticles for drug delivery. *Molecular Pharmaceutics*, 7 (6), 1913–1920. https://doi.org/10.1021/mp100253e

Goldberg, M. S. (2019). Improving cancer immunotherapy through nanotechnology. *Nature Reviews Cancer*, 19 (10), 587–602. https://doi.org/10.1038/s41568-019-0186-9

Green, M. R., Manikhas, G. M., Orlov, S., Afanasyev, B., Makhson, A. M., Bhar, P., & Hawkins, M. J. (2006). Abraxane®, a novel Cremophor®-free, albumin-bound particle form of paclitaxel for the treatment of advanced non-small-cell lung cancer. *Annals of Oncology*, 17 (8), 1263–1268. https://doi.org/10.1093/annonc/mdl104

Hainfeld, J. F., Slatkin, D. N., & Smilowitz, H. M. (2004). The use of gold nanoparticles to enhance radiotherapy in mice. *Physics in Medicine & Biology*, 49 (18), N309–N315. https://doi.org/10.1088/0031-9155/49/18/N03

Hamaguchi, T., Matsumura, Y., Suzuki, M., Shimizu, K., Goda, R., Nakamura, I., Nakatomi, I., Yokoyama, M., Kataoka, K., & Kakizoe, T. (2005). NK105, a paclitaxel-incorporating micellar nanoparticle formulation, can extend in vivo antitumour activity and reduce the neurotoxicity of paclitaxel. *British Journal of Cancer*, 92 (7), 1240–1246. https://doi.org/10.1038/sj.bjc.6602479

Hua, S., de Matos, M. B. C., Metselaar, J. M., & Storm, G. (2018). Current trends and challenges in the clinical translation of nanoparticulate nanomedicines: Pathways for translational development and commercialization. *Frontiers in Pharmacology*, 9 , Article 790. https://doi.org/10.3389/fphar.2018.00790

Huang, X., El-Sayed, I. H., Qian, W., & El-Sayed, M. A. (2006). Cancer cell imaging and photothermal therapy in the near-infrared region by using gold nanorods. *Journal of the American Chemical Society*, 128 (6), 2115–2120. https://doi.org/10.1021/ja057254a

Huang, X., Jain, P. K., El-Sayed, I. H., & El-Sayed, M. A. (2008). Plasmonic photothermal therapy (PPTT) using gold nanoparticles. *Lasers in Medical Science*, 23 (3), 217–228. https://doi.org/10.1007/s10103-007-0470-x

Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry*, 13 (10), 2638–2650. https://doi.org/10.1039/C1GC15386B

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

Jain, P. K., Huang, X., El-Sayed, I. H., & El-Sayed, M. A. (2008). Noble metals on the nanoscale: Optical and photothermal properties and some applications in imaging, sensing, biology, and medicine. *Accounts of Chemical Research*, 41 (12), 1578–1586. https://doi.org/10.1021/ar7002804

Jain, A. K., Swarnakar, N. K., Godugu, C., Singh, R. P., & Jain, S. (2011). The effect of the oral administration of polymeric nanoparticles on the efficacy and toxicity of docetaxel. *Biomaterials*, 32 (2), 503–515. https://doi.org/10.1016/j.biomaterials.2010.09.017

Jazayeri, M. H., Amani, H., Pourfatollah, A. A., Pazoki-Toroudi, H., & Sedighimoghaddam, B. (2016). Various methods of gold nanoparticles (GNPs) conjugation to antibodies. *Sensing and Bio-Sensing Research*, 9 , 17–22. https://doi.org/10.1016/j.sbsr.2016.04.002

Kesharwani, P., Jain, K., & Jain, N. K. (2014). Dendrimer as nanocarrier for drug delivery. *Progress in Polymer Science*, 39 (2), 268–307. https://doi.org/10.1016/j.progpolymsci.2013.07.005

Kim, T. Y., Kim, D. W., Chung, J. Y., Shin, S. G., Kim, S. C., Heo, D. S., Kim, N. K., & Bang, Y. J. (2004). Phase I and pharmacokinetic study of Genexol-PM, a cremophor-free, polymeric micelle-formulated paclitaxel, in patients with advanced malignancies. *Clinical Cancer Research*, 10 (11), 3708–3716. https://doi.org/10.1158/1078-0432.CCR-03-0655

Kumar, A., Zhang, X., & Liang, X. J. (2013). Gold nanoparticles: Emerging paradigm for targeted drug delivery system. *Biotechnology Advances*, 31 (5), 593–606. https://doi.org/10.1016/j.biotechadv.2012.10.002

Kumari, A., Yadav, S. K., & Yadav, S. C. (2010). Biodegradable polymeric nanoparticles based drug delivery systems. *Colloids and Surfaces B: Biointerfaces*, 75 (1), 1–18. https://doi.org/10.1016/j.colsurfb.2009.09.001

Li, H., Chen, Y., & Hu, J. (2018). Core–shell gold–polymer nanoparticles for combined photothermal and chemotherapeutic cancer therapy. *ACS Applied Materials & Interfaces*, 10 (19), 16332–16342. https://doi.org/10.1021/acsami.8b03645

Libutti, S. K., Paciotti, G. F., Byrnes, A. A., Alexander, H. R., Jr., Gannon, W. E., Walker, M., Seidel, G. D., Yuldasheva, N., & Tamarkin, L. (2010). Phase I and pharmacokinetic studies of CYT-6091, a novel PEGylated colloidal gold-rhTNF nanomedicine. *Clinical Cancer Research*, 16 (24), 6139–6149. https://doi.org/10.1158/1078-0432.CCR-10-0978

Maeda, H., Wu, J., Sawa, T., Matsumura, Y., & Hori, K. (2000). Tumor vascular permeability and the EPR effect in macromolecular therapeutics: A review. *Journal of Controlled Release*, 65 (1–2), 271–284. https://doi.org/10.1016/S0168-3659(99)00248-5

Matsumura, Y., Hamaguchi, T., Ura, T., Muro, K., Yamada, Y., Shimada, Y., Shirao, K., Okusaka, T., Ueno, H., Ikeda, M., & Watanabe, N. (2010). Phase I clinical trial and pharmacokinetic evaluation of NK911, a micelle-encapsulated doxorubicin. *British Journal of Cancer*, 103 (11), 1645–1651. https://doi.org/10.1038/sj.bjc.6605967

Mi, P. (2020). Stimuli-responsive nanocarriers for drug delivery, tumor imaging, therapy and theranostics. *Theranostics*, 10 (10), 4557–4588. https://doi.org/10.7150/thno.38069

Mitchell, M. J., Billingsley, M. M., Haley, R. M., Wechsler, M. E., Peppas, N. A., & Langer, R. (2021). Engineering precision nanoparticles for drug delivery. *Nature Reviews Drug Discovery*, 20 (2), 101–124. https://doi.org/10.1038/s41573-020-0090-8

Nikobakht, B., & El-Sayed, M. A. (2003). Preparation and growth mechanism of gold nanorods (NRs) using seed-mediated growth method. *Chemistry of Materials*, 15 (10), 1957–1962. https://doi.org/10.1021/cm020732l

O'Neill, C. L., Zhang, P., & O'Driscoll, C. M. (2018). Clinical translation of nanomedicines: Current status and future perspectives. *European Journal of Pharmaceutical Sciences*, 115 , 1–12. https://doi.org/10.1016/j.ejps.2018.01.011

Park, J., Lee, J., & Kim, K. (2016). Gold nanoparticles in polymer nanocarriers for enhanced cancer therapy. *Journal of Controlled Release*, 240 , 504–516. https://doi.org/10.1016/j.jconrel.2016.04.023

Peer, D., Karp, J. M., Hong, S., Farokhzad, O. C., Margalit, R., & Langer, R. (2007). Nanocarriers as an emerging platform for cancer therapy. *Nature Nanotechnology*, 2 (12), 751–760. https://doi.org/10.1038/nnano.2007.387

Pissuwan, D., Niidome, T., & Cortie, M. B. (2011). The forthcoming applications of gold nanoparticles in drug and gene delivery systems. *Journal of Controlled Release*, 149 (1), 65–71. https://doi.org/10.1016/j.jconrel.2009.12.006

Rao, J. P., & Geckeler, K. E. (2011). Polymer nanoparticles: Preparation techniques and size-control parameters. *Progress in Polymer Science*, 36 (7), 887–913. https://doi.org/10.1016/j.progpolymsci.2011.01.001

Rastinehad, A. R., Anastos, H., Wajswol, E., Winoker, J. S., Sfakianos, J. P., Doppalapudi, S. K., Carrick, M. R., Knauer, C. J., Taouli, B., Lewis, S. C., Tewari, A. K., Schwartz, J. A., Canfield, S. E., George,

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

Scilit

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 11-19.
doi: https://doi.org/10.33687/ricosbiol.04.03.113

A. K., & Walsh, P. C. (2019). Gold nanoshell-localized photothermal ablation of prostate tumors in a clinical pilot device study. *Proceedings of the National Academy of Sciences*, 116 (37), 18590–18596. https://doi.org/10.1073/pnas.1906929116

Singh, P., Pandit, S., Mokkapati, V. R. S. S., Garg, A., Ravikumar, V., & Mijakovic, I. (2020). Gold nanoparticles in diagnostics and therapeutics for human cancer. *International Journal of Molecular Sciences*, 21 (7), Article 2592. https://doi.org/10.3390/ijms21072592

Soppimath, K. S., Aminabhavi, T. M., Kulkarni, A. R., & Rudzinski, W. E. (2001). Biodegradable polymeric nanoparticles as drug delivery devices. *Journal of Controlled Release*, 70 (1–2), 1–20. https://doi.org/10.1016/S0168-3659(00)00339-4

Sperling, R. A., Rivera Gil, P., Zhang, F., Zanella, M., & Parak, W. J. (2008). Biological applications of gold nanoparticles. *Chemical Society Reviews*, 37 (9), 1896–1908. https://doi.org/10.1039/B712170A

Suk, J. S., Xu, Q., Kim, N., Hanes, J., & Ensign, L. M. (2016). PEGylation as a strategy for improving nanoparticle-based drug and gene delivery. *Advanced Drug Delivery Reviews*, 99 (Pt A), 28–51. https://doi.org/10.1016/j.addr.2015.09.012

Sung, H., Ferlay, J., Siegel, R. L., Laversanne, M., Soerjomataram, I., Jemal, A., & Bray, F. (2021). Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA: A Cancer Journal for Clinicians*, 71 (3), 209–249. https://doi.org/10.3322/caac.21660

Tinkle, S., McNeil, S. E., Mühlebach, S., Bawa, R., Borchard, G., Barenholz, Y. C., Tamarkin, L., & Desai, N. (2014). Nanomedicines: Addressing the scientific and regulatory gap. *Annals of the New York Academy of Sciences*, 1313 (1), 35–56. https://doi.org/10.1111/nyas.12403

Turkevich, J., Stevenson, P. C., & Hillier, J. (1951). A study of the nucleation and growth processes in the synthesis of colloidal gold. *Discussions of the Faraday Society*, 11 , 55–75. https://doi.org/10.1039/DF9511100055

Wang, S., Huang, P., & Chen, X. (2019). Stimuli-responsive nanomaterials for cancer therapy. *Advanced Materials*, 31 (9), Article 1805575. https://doi.org/10.1002/adma.201805575

Yang, Q., Lai, S. K., & Wang, Y. (2016). Polyethylene glycol–mediated steric stabilization of nanoparticles: Understanding the mechanisms and implications for drug delivery. *WIREs Nanomedicine and Nanobiotechnology*, 8 (5), 742–759. https://doi.org/10.1002/wnan.1387

Zhuang, L., Chen, Y., & Zhang, H. (2025). Multifunctional gold nanoparticles: Bridging detection, diagnosis, and targeted therapy in cancer. *Molecular Cancer*, 24 (1), Article 228. https://doi.org/10.1186/s12943-025-02431-6

Data Availability Statement

No original datasets were generated for this review article. All cited data and findings are available within the original research publications referenced in the manuscript, accessible via the provided Digital Object Identifiers (DOIs) or through respective journal platforms.

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 20-25.
doi: https://doi.org/10.33687/ricosbiol.04.03.111

Review Article

Polymers as Immobilizing Matrices for Enhanced Antimicrobial Production in Biofermentors: A Critical Review

Abeer Abd Elhadi[1], *Abouelhag H. A.*[2]*

[1]Department of Chemistry of Natural and Microbial Products, National Research Centre, Dokki, Egypt, 12622.
[2]Department of Microbiology and Immunology, National Research Centre, Dokki, Egypt, 12622.

Received: 01-03-2026 **Accepted:** 22-03-2026 **Published online:** 30-03-2026
DOI: https://doi.org/10.33687/ricosbiol.04.03.111

Abstract

The escalating crisis of antimicrobial resistance (AMR) demands innovative production platforms for both existing and novel antimicrobial compounds. Biofermentors are central to the industrial manufacturing of these agents, yet conventional free-cell fermentation suffers from inherent limitations such as low volumetric productivity, product inhibition, cell washout in continuous processes, and high downstream processing costs. Cell immobilization using polymer matrices has emerged as a powerful strategy to overcome these bottlenecks by retaining high cell densities, enabling continuous operation, and simplifying product recovery. This review critically examines the role of natural, synthetic, and composite polymers as immobilizing agents in biofermentors for antimicrobial production. The fundamental mechanisms of immobilization—entrapment, adsorption, covalent binding, encapsulation, and biofilm formation—are discussed alongside key polymer selection criteria. Recent applied uses are highlighted, including continuous nisin production with *Lactococcus lactis* immobilized in alginate-polyvinyl alcohol (PVA) composite beads, penicillin V production using *Penicillium chrysogenum* biofilms on polyurethane foam, and recyclable magnetic alginate microspheres for actinorhodin production. Challenges such as mass-transfer limitations, polymer stability, and scale-up difficulties are critically analyzed. Future perspectives emphasize stimuli-responsive polymers, 3D-printed scaffolds, and computational modeling to enable next-generation immobilized fermentation platforms. By integrating polymer science with bioreactor engineering, immobilized cell technology offers a sustainable path toward more efficient antimicrobial manufacturing.

Keywords: Antimicrobial production, biofermentors, cell immobilization, polymer matrices, alginate, polyvinyl alcohol, chitosan, biopolymers, continuous fermentation, bacteriocins, antibiotics, antimicrobial resistance, bioreactor design, immobilized cell technology.

Introduction

The global burden of antimicrobial resistance (AMR) has reached critical levels, with an estimated 1.27 million deaths directly attributable to bacterial AMR in 2019 (Murray et al., 2022). The diminishing pipeline of new antibiotics underscores the urgent need for both novel antimicrobial agents and more efficient production processes for existing ones. Biofermentors—ranging from submerged stirred-tank reactors to solid-state fermentation systems—are the primary workhorses for producing antimicrobial compounds from microorganisms such as *Streptomyces*, *Bacillus*, *Lactobacillus*, *Penicillium*, and *Aspergillus* (Bhatia et al., 2021).

Despite their widespread use, conventional free-cell fermentation faces several drawbacks. Batch processes suffer from low productivity due to substrate and product inhibition, while continuous processes are hampered by cell washout and genetic instability of producer strains (Kourkoutas et al., 2004). Additionally, the separation of biomass from the fermentation broth adds significant downstream processing costs.

Cell immobilization—the physical confinement or attachment of whole cells to or within a solid support—offers a compelling solution to these challenges (Eş et al., 2015). Immobilized systems enable high cell densities, protect cells from shear stress, allow continuous operation for extended periods, and facilitate simplified product

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 20-25.
doi: https://doi.org/10.33687/ricosbiol.04.03.111

recovery (Willaert & Baron, 2020). The choice of immobilization matrix is critical, and polymers have emerged as the most versatile and widely used materials. Polymers provide the structural architecture and functional microenvironment that determine cell viability, metabolic activity, mass transfer, and overall bioprocess performance.

This review provides a critical and comprehensive analysis of polymers used as immobilizing agents for antimicrobial production in biofermentors. It covers the classification and properties of natural, synthetic, and composite polymers, the mechanisms and techniques of immobilization, integration with bioreactor configurations, and recent applied advances in producing bacteriocins, antibiotics, and antifungal compounds. Challenges and future directions are also discussed to guide the rational design of next-generation immobilized fermentation platforms.

1. Fundamentals of Cell Immobilization in Fermentors

1.1. Mechanisms of Immobilization

Cells can be immobilized via several distinct mechanisms, each with its own advantages and limitations:

- **Covalent binding:** Cells are attached to polymer surfaces through covalent bonds, typically using functionalized carriers (e.g., amino- or carboxyl-modified polymers). This method provides strong attachment but may reduce cell viability due to harsh coupling conditions (Brena et al., 2013).
- **Adsorption:** Physical attachment via van der Waals forces, hydrogen bonding, or ionic interactions. It is simple, reversible, and mild but often suffers from cell leakage over time (Bayat & Hassanshahian, 2020).
- **Entrapment:** Cells are confined within a porous polymer network (e.g., alginate, polyvinyl alcohol hydrogels). This method offers good protection and high cell loading but may impose mass-transfer limitations (Cassidy et al., 1996).
- **Encapsulation:** Cells are enclosed within a semi-permeable polymer membrane. This provides a controlled microenvironment and is particularly useful for protecting cells from toxic products (Burgain et al., 2011).
- **Biofilm formation:** Cells naturally colonize the surface of inert polymer supports (e.g., polyurethane foam, cellulose carriers), forming robust biofilms that can sustain long-term activity (Wang et al., 2022).

1.2. Key Parameters for Polymer Selection

Selecting an appropriate polymer is critical for successful immobilization. Key parameters include:

- **Biocompatibility and non-toxicity:** The polymer must not harm the producer strain.
- **Mechanical stability:** Resistance to shear forces, pH fluctuations, and temperature variations during fermentation (Datta et al., 2020).
- **Porosity and diffusivity:** Adequate pore size to allow nutrient influx and product efflux.
- **Chemical functionality:** Availability of functional groups for derivatization or enhanced cell adhesion (Gómez et al., 2021).
- **Cost, availability, and reusability:** Economic feasibility for industrial application.

2. Classification and Properties of Polymers Used as Immobilizing Agents

2.1. Natural Polymers

Alginate: Extracted from brown algae, alginate is the most widely used polymer for entrapment due to its mild gelation with divalent cations (e.g., Ca^{2+}) and excellent biocompatibility. However, its mechanical stability is limited, and it is susceptible to degradation in phosphate-containing media. To overcome these limitations, alginate is often blended with other polymers or cross-linked with silica (López et al., 2021).

Chitosan: A cationic polysaccharide derived from chitin, chitosan exhibits inherent antimicrobial activity. While this can help reduce contamination, it may also stress the producer strain. Chitosan is frequently used for adsorption and as a coating for other matrices (Rabea et al., 2003). Chitosan-coated alginate beads have been successfully employed for bacteriocin production (Zhou et al., 2020).

Carrageenan, agarose, and cellulose: These polysaccharides form gels or fibrous structures suitable for cell immobilization. Cellulose-based carriers are particularly effective for biofilm cultures of filamentous microorganisms (El-Hadi et al., 2024).

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 20-25.
doi: https://doi.org/10.33687/ricosbiol.04.03.111

Gelatin: A protein derived from collagen, gelatin is biocompatible but lacks mechanical stability. It is often cross-linked with glutaraldehyde or genipin for improved performance (Jafari et al., 2021).

2.2. Synthetic Polymers

Polyvinyl alcohol (PVA): PVA is increasingly popular due to its high mechanical strength, chemical stability, and non-toxicity. PVA cryogels (e.g., Lentikats®) offer macroporous structures with excellent mass transfer. PVA-alginate composites have demonstrated remarkable stability in long-term continuous fermentations (Khatami et al., 2022).

Polyurethane (PU) foams: Pre-formed porous supports ideal for biofilm immobilization. Their open-pore structure allows efficient oxygen transfer, making them suitable for aerobic fermentations such as penicillin production (Wang et al., 2022).

Polyethylene glycol (PEG): Used in hydrogels and as a surface-modifying agent to reduce protein adsorption and improve biocompatibility (Datta et al., 2020).

Polycaprolactone (PCL): A biodegradable polyester employed in electrospun nanofibers for enzyme and cell immobilization (Sahoo et al., 2021).

2.3. Composite and Hybrid Materials

- **Alginate-PVA blends:** Combine the biocompatibility of alginate with the mechanical robustness of PVA. Used for nisin production in continuous packed-bed reactors (Silva et al., 2023).
- **Magnetic composites:** Incorporation of Fe_3O_4 nanoparticles enables easy recovery and reuse of immobilized biocatalysts via magnetic separation (Liu et al., 2024).
- **Functionalized polymers:** Polymers grafted with carboxyl, amine, or epoxy groups enhance cell adhesion and create affinity for specific antimicrobial products (Gómez et al., 2021).

3. Immobilization Techniques and Bioreactor Integration

3.1. Immobilization Methods

- **Gelation/extrusion:** Droplet formation for bead production (e.g., alginate, carrageenan).
- **Electrospinning:** Produces nanofibrous scaffolds with high surface area for cell adhesion (Sahoo et al., 2021).
- **Cryogelation:** Creates macroporous PVA matrices with excellent permeability and elasticity (Khatami et al., 2022).
- **Encapsulation:** Co-extrusion or emulsion techniques for microcapsules with a polymer shell (Burgain et al., 2011).

3.2. Bioreactor Configurations

- **Packed-bed reactors (PBR):** High cell density but risk of clogging and mass-transfer gradients. Used successfully for continuous bacteriocin production (Silva et al., 2023).
- **Fluidized-bed reactors (FBR):** Better mixing and reduced clogging; suitable for soft beads and biofilm carriers (Wang et al., 2022).
- **Stirred-tank reactors (STR):** Conventional but can cause shear damage; require robust polymer matrices or protective cages (Eş et al., 2015).
- **Air-lift reactors:** Gentle mixing, ideal for shear-sensitive immobilized systems (Burgain et al., 2011).

4. Recent Applied Uses in Antimicrobial Production

4.1. Bacteriocins (Nisin, Pediocin, etc.)

Nisin, a lantibiotic produced by *Lactococcus lactis*, is widely used as a food preservative. Free-cell fermentation suffers from product inhibition and low productivity. Immobilization has proven highly effective. Silva et al. (2023) reported stable nisin production for over 30 days in a packed-bed reactor using *L. lactis* entrapped in alginate-PVA composite beads. Volumetric productivity was four-fold higher than in free-cell batch cultures. At pilot scale, Zhou et al. (2020) used a 50-L fluidized-bed reactor with chitosan-coated alginate beads for pediocin production, demonstrating industrial feasibility.

4.2. Antibiotics (Penicillins, Tetracyclines, Actinomycins)

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 20-25.
doi: https://doi.org/10.33687/ricosbiol.04.03.111

Penicillin V production by *Penicillium chrysogenum* requires high oxygen transfer. Wang et al. (2022) immobilized the fungus as biofilms on reticulated polyurethane foam in a fluidized-bed reactor. The system operated continuously for 40 days with minimal productivity loss, attributed to the open-pore structure of the foam ensuring adequate oxygen supply. For actinorhodin, Liu et al. (2024) developed magnetic alginate microspheres containing *Streptomyces coelicolor*. The immobilized cells were recovered and reused in five successive batches, reducing production costs by approximately 30%.

4.3. Antifungal Lipopeptides (Iturin, Fengycin)

Bacillus subtilis produces antifungal lipopeptides such as iturin A. El-Hadi et al. (2024) used a novel cellulose-nanofiber carrier in a packed-bed reactor, achieving a six-fold increase in volumetric productivity compared to free-cell fermentation. The system maintained activity for 21 days, demonstrating the potential of natural fiber carriers for fungal pathogen control.

4.4. Antimicrobial Peptides (AMPs) from Recombinant Hosts

Recombinant production of antimicrobial peptides (AMPs) in *Escherichia coli* is often limited by toxicity of the product to the host. Jafari et al. (2021) encapsulated recombinant *E. coli* producing an AMP in genipin-crosslinked gelatin-alginate microcapsules. The polymer shell prevented leakage of the toxic peptide into the bulk medium while allowing nutrient diffusion, leading to a three-fold increase in yield compared to free cells.

5. Critical Challenges and Limitations

5.1. Mass Transfer Limitations

The polymer matrix can create gradients of oxygen, nutrients, and pH, particularly in large beads or dense biofilms. This leads to cell heterogeneity and reduced overall productivity. Strategies to mitigate these limitations include the use of macroporous matrices (e.g., PVA cryogels, polyurethane foam) and reduction of bead size (Khatami et al., 2022).

5.2. Polymer Stability and Longevity

Alginate beads are prone to degradation in phosphate-containing media, limiting their use in complex fermentation broths. Synthetic polymers such as PVA offer superior stability but may be more expensive. Composite materials aim to balance stability with biocompatibility (Datta et al., 2020).

5.3. Scale-Up Difficulties

Maintaining homogeneous mixing, bead integrity, and sterility in large-scale bioreactors remains challenging. Computational fluid dynamics (CFD) modeling is increasingly used to design scalable systems and predict mass-transfer behavior (Gómez et al., 2021).

5.4. Economic Viability

The additional costs of polymers, immobilization processes, and specialized bioreactors must be justified by increased productivity and simplified downstream processing. Life-cycle assessments are needed to evaluate the true economic benefits (Silva et al., 2023).

6. Future Perspectives and Emerging Trends

6.1. Smart and Stimuli-Responsive Polymers

Polymers that respond to pH, temperature, or specific metabolites can enable on-demand cell release or product recovery. Early studies with PNIPAM-based hydrogels show promise for controlled fermentation (López et al., 2021).

6.2. 3D Printing and Additive Manufacturing

Additive manufacturing allows precise control of scaffold architecture, enabling customized pore networks for optimal mass transfer and cell colonization (Sahoo et al., 2021).

6.3. Electro-Fermentation with Conductive Polymers

Conductive polymers (e.g., polypyrrole, PEDOT) can be used to stimulate microbial metabolism through direct electron transfer, enhancing secondary metabolite production (Bhatia et al., 2021).

6.4. Co-immobilization of Microbial Consortia

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 20-25.
doi: https://doi.org/10.33687/ricosbiol.04.03.111

Defined co-cultures immobilized in structured polymers can exploit synergistic interactions for enhanced antimicrobial production (El-Hadi et al., 2024).

6.5. Computational Modeling

CFD and mass-transfer models will accelerate rational design of immobilization matrices and bioreactors for scale-up, reducing empirical trial-and-error (Gómez et al., 2021).

Conclusion

Polymers play an indispensable role in advancing cell immobilization for antimicrobial production. By enabling high-density, continuous fermentation with simplified downstream processing, polymer-immobilized systems address the key limitations of conventional free-cell processes. Recent applied studies demonstrate the successful translation of natural polymers (alginate, chitosan), synthetic polymers (PVA, polyurethane), and composites for producing bacteriocins, antibiotics, and antifungal compounds at scales approaching industrial relevance. However, challenges such as mass-transfer limitations, polymer stability, and scale-up must be addressed through rational design and integration with advanced bioreactor configurations. Future progress will rely on smart polymers, 3D-printed scaffolds, and computational modeling to unlock the full potential of immobilized fermentation, ultimately contributing to a sustainable and efficient antimicrobial manufacturing pipeline.

References

Ahmad, N., & Rani, R. (2023). Recent advances in polymeric matrices for enzyme immobilization: A focus on antimicrobial production. *Journal of Polymers and the Environment, 31* (4), 1289–1306. https://doi.org/10.1007/s10924-022-02689-5

Bayat, Z., & Hassanshahian, M. (2020). Immobilization of microorganisms for bioremediation: Techniques, carriers, and applications. *Journal of Hazardous Materials, 392*, Article 122382. https://doi.org/10.1016/j.jhazmat.2020.122382

Bhatia, S. K., Bhatia, R. K., Yang, Y. H., & Ahn, J. (2021). Bioprocessing of antibiotics: Current trends and future perspectives. *Bioresource Technology, 321*, Article 124472. https://doi.org/10.1016/j.biortech.2020.124472

Brena, B., González-Pombo, P., & Batista-Viera, F. (2013). Immobilization of enzymes: A literature survey. In J. M. Guisan (Ed.), *Immobilization of enzymes and cells* (pp. 15–31). Humana Press. https://doi.org/10.1007/978-1-62703-550-7_2

Burgain, J., Gaiani, C., Linder, M., & Scher, J. (2011). Encapsulation of probiotic living cells: From laboratory scale to industrial applications. *Journal of Food Engineering, 104* (4), 467–483. https://doi.org/10.1016/j.jfoodeng.2010.12.031

Cassidy, M. B., Lee, H., & Trevors, J. T. (1996). Environmental applications of immobilized microbial cells: A review. *Journal of Industrial Microbiology, 16* (2), 79–101. https://doi.org/10.1007/BF01570068

Costa, S. A., Azevedo, A. M., & Prazeres, D. M. F. (2022). Protein and cell immobilization in biotechnology: Current strategies and applications. *Biotechnology Advances, 55*, Article 107909. https://doi.org/10.1016/j.biotechadv.2022.107909

Datta, S., Christena, L. R., & Rajaram, Y. R. S. (2020). Enzyme immobilization: An overview on techniques and support materials. 3 Biotech, *10* (5), Article 235. https://doi.org/10.1007/s13205-020-02129-8

El-Hadi, A. A., Mohamed, S. S., & Abd El-Aziz, A. M. (2024). Cellulose nanofiber-based carriers for enhanced iturin A production by *Bacillus subtilis* in continuous fermentation. *Carbohydrate Polymers, 323*, Article 121419. https://doi.org/10.1016/j.carbpol.2023.121419

Eş, I., Vieira, J. D. G., & Amaral, A. C. (2015). Principles, techniques, and applications of biocatalyst immobilization for industrial application. *Applied Microbiology and Biotechnology, 99* (5), 2065–2082. https://doi.org/10.1007/s00253-015-6390-y

García-Martínez, T., & González-Benito, J. (2024). Hybrid polymer-nanoparticle systems for biocatalyst immobilization: Prospects for antimicrobial fermentation. *ACS Applied Bio Materials, 7* (2), 567–582. https://doi.org/10.1021/acsabm.3c00892

Gómez, J. M., López, C., & Deive, F. J. (2021). Functionalized polymer carriers for microbial cell immobilization: A review. *Journal of Chemical Technology & Biotechnology, 96* (8), 2121–2133. https://doi.org/10.1002/jctb.6754

Jafari, M., Mehdinejad, M., & Rahimi, F. (2021). Encapsulation of recombinant *Escherichia coli* producing antimicrobial peptide in genipin-crosslinked gelatin-alginate microcapsules. *International Journal of Biological Macromolecules, 183*, 1452–1461. https://doi.org/10.1016/j.ijbiomac.2021.05.114

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 20-25.
doi: https://doi.org/10.33687/ricosbiol.04.03.111

Khatami, S. H., Vakili, M., & Yazdian, F. (2022). Polyvinyl alcohol cryogels as promising matrices for cell immobilization in bioprocesses: A review. *Bioprocess and Biosystems Engineering, 45* (3), 417–434. https://doi.org/10.1007/s00449-021-02667-w

Kourkoutas, Y., Bekatorou, A., Banat, I. M., Marchant, R., & Koutinas, A. A. (2004). Immobilization technologies and support materials suitable in alcohol beverages production: A review. *Food Microbiology, 21* (4), 377–397. https://doi.org/10.1016/j.fm.2003.10.005

Li, J., & Wang, Z. (2025). Stimuli-responsive hydrogels for controlled release in microbial fermentation: A perspective. *Current Opinion in Chemical Engineering, 38*, Article 100914. https://doi.org/10.1016/j.coche.2024.100914

Liu, X., Zhang, Y., & Wang, H. (2024). Magnetic alginate microspheres for recyclable immobilization of *Streptomyces coelicolor* in actinorhodin production. *Biochemical Engineering Journal, 192*, Article 108850. https://doi.org/10.1016/j.bej.2023.108850

López, C., Gómez, J. M., & Deive, F. J. (2021). Alginate-silica hybrid materials as robust supports for cell immobilization in antibiotic production. *Materials Science and Engineering: C, 121*, Article 111854. https://doi.org/10.1016/j.msec.2020.111854

Murray, C. J., Ikuta, K. S., Sharara, F., Swetschinski, L., Robles Aguilar, G., Gray, A., … & Naghavi, M. (2022). Global burden of bacterial antimicrobial resistance in 2019: A systematic analysis. *The Lancet, 399* (10325), 629–655. https://doi.org/10.1016/S0140-6736(21)02724-0

Patel, A. K., Singhania, R. R., & Pandey, A. (2023). Biofilm reactors for value-added products: A review on current trends. *Bioresource Technology Reports, 21*, Article 101334. https://doi.org/10.1016/j.biteb.2022.101334

Rabea, E. I., Badawy, M. E. T., Stevens, C. V., Smagghe, G., & Steurbaut, W. (2003). Chitosan as antimicrobial agent: Applications and mode of action. *Biomacromolecules, 4* (6), 1457–1465. https://doi.org/10.1021/bm034130m

Sahoo, S., Chakraborti, C. K., & Behera, P. K. (2021). Electrospun nanofibrous scaffolds for immobilization of enzymes and microbial cells: A review. *Journal of Industrial and Engineering Chemistry, 104*, 1–16. https://doi.org/10.1016/j.jiec.2021.08.023

Silva, F. A., Queirós, P., & Teixeira, J. A. (2023). Continuous nisin production with *Lactococcus lactis* immobilized in alginate-PVA composite beads: A pilot-scale study. *Food and Bioproducts Processing, 138*, 45–55. https://doi.org/10.1016/j.fbp.2023.01.002

Wang, L., Zhang, H., & Chen, X. (2022). Biofilm immobilization of *Penicillium chrysogenum* on polyurethane foam for continuous penicillin V production. *Bioresource Technology, 346*, Article 126588. https://doi.org/10.1016/j.biortech.2021.126588

Willaert, R. G., & Baron, G. V. (2020). The application of cell immobilization in the food industry. In C. Webb & J. F. T. Spencer (Eds.), *Immobilized cells* (pp. 299–334). Springer. https://doi.org/10.1007/978-3-642-55942-6_11

Zhou, Y., Li, W., & Wang, T. (2020). Chitosan-coated alginate beads for pediocin production by *Pediococcus acidilactici* in a fluidized-bed bioreactor. *Process Biochemistry, 99*, 267–275. https://doi.org/10.1016/j.procbio.2020.09.008

Data Availability Statement

No original datasets were generated for this review article. All cited data and findings are available within the original research publications referenced in the manuscript, accessible via the provided Digital Object Identifiers (DOIs) or through respective journal platforms.

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Abouelhag H. A.*
ha.abouelhag@nrc.sci.eg
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

Research Article

Impact of plastic pollution on fresh water biota of water streams around the picnic spots of Hilly region in the Swat Valley Pakistan

Murad Khan[1], Wisal Muhammad khan[1], Shujaul Mulk Khan[2]
[1]Department of Botany, Islamia College University Peshawar Pakistan
[2]Department of Plant Sciences, Quaid-i-Azam University Islamabad Pakistan

Received: 09-03-2026 **Accepted:** 22-03-2026 **Published online:** 30-03-2026
DOI: https://doi.org/10.33687/ricosbiol.04.03.110

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Abstract

The presence of Blue water Ecosystem in the upper region of Swat has a diverse biomass of different species at different trophic levels. Among species involved in the food chain of these freshwater systems are *Navicula subtilissima, Zygnema Cruciatum* (Producer), *Lathocerus americanus* and other aquatic insects (Primary Consumer) of low temperature and *Schizothorax plagiostomus (*Secondary consumer*)*. There is a drastic imbalance and disturbance in their communities due to water pollution. Plastic bottles are on top among the pollutants which are thrown by visitors especially at the picnic spots around these water bodies. Fish species have been observed to emigrate from the picnic spots towards deep, speedy and clean habitats in these aquatic ecosystems. Decomposition rate of these bottles is negligible and hence affecting aquatic fauna and flora Food in a very negative manner. Heavy metal concentrations in pristine, unpolluted waters of this region are typically below detectable levels (0%). However, in winter 2019-2020, following the accumulation of plastic waste, this figure was recorded at 13%, indicating a significant increase. Due to such pollution this figure recorded in winter 2019-2020 was 13 % with an increasing trend. Regulatory authorities must pay attention to this issue on priority base and initiate remedial as well as preventive measures for the water of uphill beautiful streams and lakes.

Keywords: Plastic Bottles, Pollution, Swat Valley, Freshwater Ecosystem.

Introduction

Plastics are used extensively for a wide range of applications, with approximately 280 million tons produced annually worldwide for products such as food packaging and other materials (Shaw & Sahni, 2014; Sigler, 2014). The occurrence of plastic trashes has become a well-researched “hot topic” in the marine environment, but is ignored in freshwater environments (Wagner et al., 2014 and Eerkes-Medrano et al., 2015). Plastics in different form found in already sufficient quantities to be considered as one of the most important types of “techno fossil” that can form a permanent record of human presence on Earth (Zalasiewicz et al. 2016). From the last century, humans have been muddling near water resources, causing plastic pollution alarmingly (Faure et al. 2015). In the List of Crucial environmental problems Plastic pollution are numbered (UNEP 2014), and it is notorious alongside climate change as an evolving issue that influence human health in long and biological diversity in the short term future (Sutherl, et al. 2010).

Studies have shown plastic absorption by wild freshwater organisms (e.g. Sanchez et al., 2014, Faure et al., 2015, Biginagwa et al., 2016; Pazos et al., 2017). Plastic concentrations have been reported in different water bodies i-e rivers (e.g. Lechner et al., 2014; Klein et al., 2015), lakes (e.g. Fischer et al., 2016; Blettler et al., 2017), estuaries (e.g. Peng et al., 2017) and even on wastewater as well (Mintenig et al., 2017; Correia Prata, 2018). Moreover, freshwater plastic research seems to be inherently partial towards a country's state of development and disconnected as each study was considered and conducted with its specific aims in mind (Blettler et al. 2018).

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

Scilit

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

Water quality problems are a major challenge that humanity is facing in the twenty-first century as it directly and indirectly emphasizes them (Schwarzenbach et al., 2010). it was noticed that microplastics is more likely to infiltrate food webs (Browne et al. 2008). Studies have shown that freshwater invertebrates and vertebrates can ingest plastic particles, causing serious illness from cellular to all systems of the body that compel them for migration (e.g., Rosenkranz et al. 2009, Imhof et al. 2013, Sanchez et al. 2014; Biginagwa et al. 2016). As many plastics are chemically harmful, either because they are harmful or because they absorb other pollutants that are harmful for the Producers (Algae) of the Area (Teuten et al. 2009; Rochman et al. 2013).

Figure 2a: Stable Ecosystem 2018(autumn)

Figure 1b: Stable Ecosystem 2018(autumn)

Figure (1c): Disturbed Ecosystem April (2020) After Plastic Bottle Pollution

Material and method

STUDY AREA:

The river swat with all of its Cascades and others originates from Hindukush Mountains above Kalam (Mahoodand) and empties in River Kabul near Charsadda district, and is 240 Km long. It is also stated in Rig Veda 8.19.37 as the Suvastu River (Swat River) (Lal, 2005).. A large number of peoples in different way are dependent on the river for their maintenance and many societies use its water for drinking , for field and in last for generating power . It is also the prime source for fishing, construction material and irrigation (Shah et al., 2016).

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Figure (2):Study Area Map (River Swat)

Sampling and Identification

Due to diversity of organisms (Algae, Insect and Fishes) in the research so different methods applied in different spots.

Algal collection

Algae (Producer) collection was made by planktonic net, scooping Vegetation of the Ecosystem and by water collection from that spot.

Algal identification

The Algal members were identified from available literature (G.W Prescott 1954) and Seamer D 2017.

Insects Collection

Insects were collected from the samples collection randomly from the water in the ecosystem by collecting water after Shaking in particular water part

Insect Identification

Insect were identified from available Literature (Pond Life) by George K. Reid Paperback

Fishes Collection

Fishes were collected by Fishery net and by locale people using method by showing a little piece of breed in Pot and collect fishes.

Fishes Identification

The Species were identified from the available literature for Fishes (Heckel 1838; Leidy, 1847) for Insects in chain.

RESULT AND DISCUSSION

Water a basic source of life , important from cellular Level to Habitat of all kind of Flora and Fauna on the earth. The Assurance of water is actually the surety of Life.

The classification of life in Aquatic environment is all because of the Nature of that water weather it is Fresh, Marine or Brackish water.The equilibrium of the cell is a Primary need for every life.Life on the earth is not in isolated form, All the organisms are linked in any form with in an ecosystem. Fresh water also have an ecosystem of different water the current studies was conducted in the Hilly region picnic spot of the Swat.

Before the exploring of the study area and before the arrival of the plastic pollutants (Water bottles, soft drink bottles and some others) The Algal Member *Zygnema Cruciatum* dominating the Lentic water with Blooms appearance and the greenery of the place presenting the water status visually.

The slippery nature of the rocks and stones present the presence of the *Navicula subtilissima*.

The fly(Primery consumer) surrounding this fresh water ecosystem is dominating by *Lathocerus americanus*.present there in rocks and Blooms there.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net
© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

The (Secondary consumer) *Schizothorax plagiostomus* were collected by Fishery Net use by the Local Fisher mans . All the above statements were collected in Spring 2018, after a gap of two years and the arrival of pollutant there a abrupt change in trophic level was observed, the bloom were totally disturbed with no regular body , instead they were collected in different corners of the ecosystem.

The White fly was collected approximately 200 meter away from the ecosystem with a small water fall presenting the absence of Plastic water bottles.

No single species of *Schizothorax plagiostomus* was collected in that Lentic Ecosystem and were collected in the deep water of River swat away 400metre away.

The data, numbers, colonies, members, and status of the ecosystem present the pollutants function there negatively and show how this 16000 square feet ecosystem was disturbed by polluting only with plastics bottles.

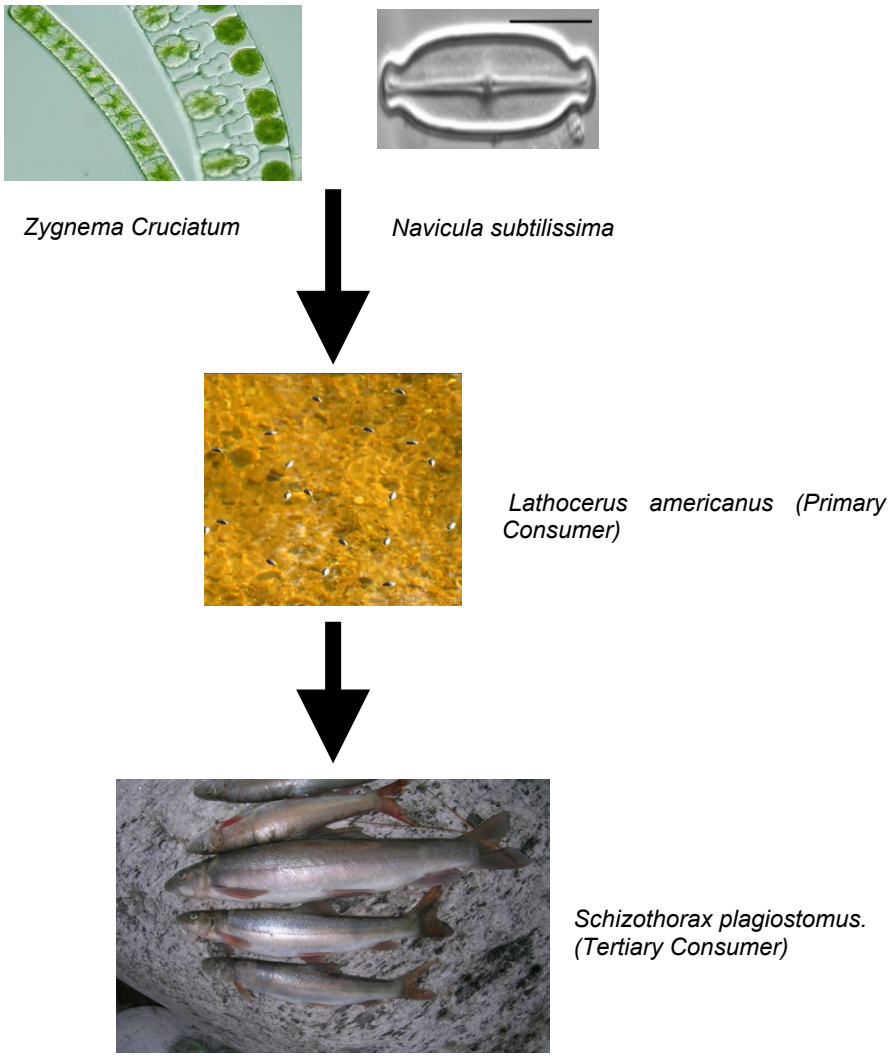

Figure (3): Plastic degradation process

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

Table (1): Water quality difference between the migrated habitats.

Abiotic Factor	Natural Habitat(Before Pollutant)	Natural Habitat(After Pollutant)
Temperature	9-12	13
PH	7.2	7
Electric conductivity	402.4	407
Salinity	0.2	0.3
Dissolved oxygen	43.2	42.2
Light intensity	1127	1022
Depth of Water (Max)	3 -4 ft	8- 11+

Table (2): Collection of Fishes in different time of the day in picnic spot before pollution(2018)

Collection time	Maximum	Minimum	Average
4:00Am	7/fishing net	5/fishing net	6/fishing net
10:00Am	4/fishing net	2/fishing net	3/fishing net
2:00Pm	2/fishing net	0/fishing net	1/fishing net
4:00Pm	1/fishing net	1/fishing net	1/fishing net

Table (3): Collection of Fishes in different time of the day in picnic spot after pollution (2020)

Collection time	Maximum	Minimum	Average
4:00Am	2/fishing net	1/fishing net	1.5/fishing net
10:00Am	1/fishing net	0/fishing net	.5/fishing net
2:00Pm	0/fishing net	0/fishing net	0/fishing net
4:00Pm	0/fishing net	0/fishing net	0/fishing net

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

Copyright: Copyrights retained to the Authors., Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

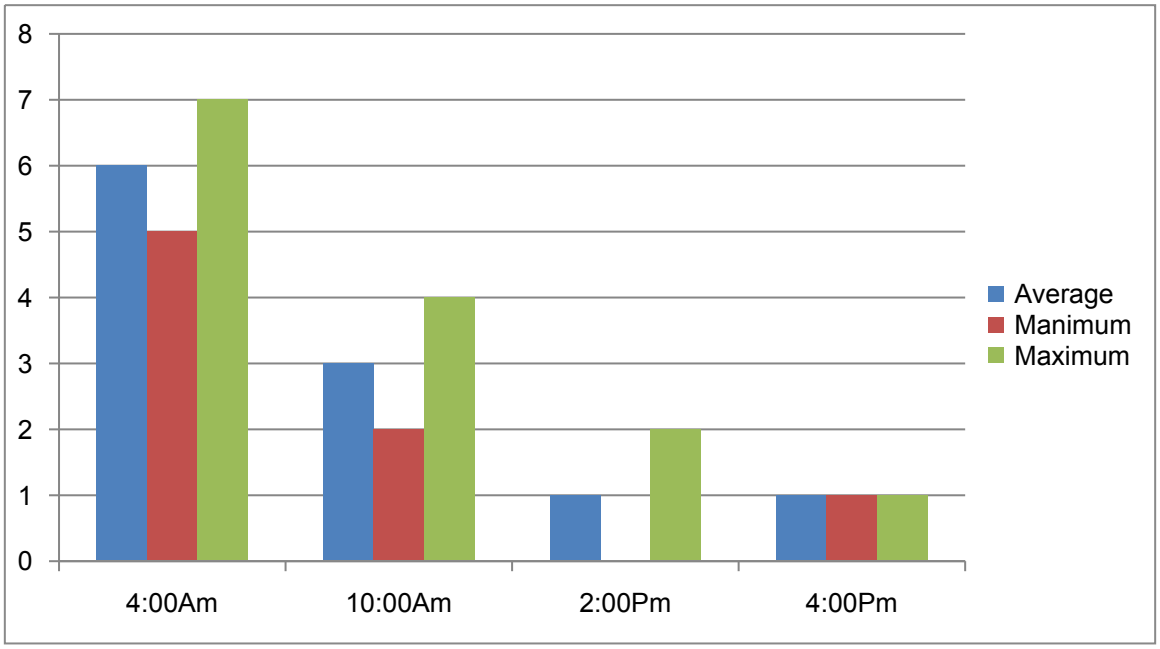

Fig 04: Collection of Fishes in different time of the day in picnic spot before pollution (2018)

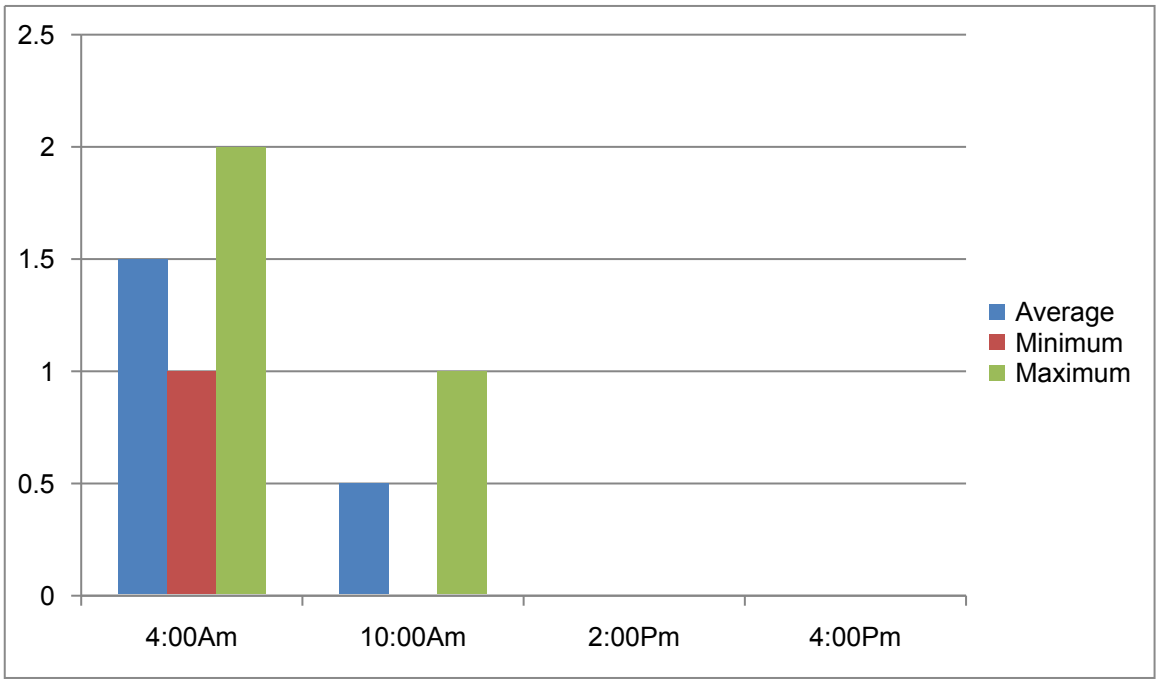

Fig (5): Collection of Fishes in different time of the day in picnic spot after pollution (2020)

Results and Discussion

The current study aimed to assess the impact of plastic bottle pollution on a freshwater ecosystem in the Swat Valley by comparing the biotic community structure and key abiotic parameters before (2018) and after

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net
© 2026 Copyright by the Author

Scilit

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

(2020) the significant accumulation of plastic waste at a popular picnic spot. The results revealed a marked disturbance in the ecosystem, with observable negative effects across all trophic levels.

1. Changes in Biotic Community Structure

The most conspicuous change was the dramatic alteration of the producer and consumer communities within the 16,000 square feet study area.

Producers: In 2018, the ecosystem was characterized by a healthy and stable community of producers. The presence of *Zygnema cruciatum* in bloom-forming colonies and the dominant coverage of *Navicula subtilissima* indicated a productive and balanced aquatic environment. The "greenery" and "slippery nature of the rocks" noted in the methods were visual confirmations of this robust algal growth. In contrast, the 2020 survey showed that these blooms were "totally disturbed with no regular body." The algal colonies were fragmented and relegated to "different corners of the ecosystem," signifying a collapse of the primary producer community. This decline can be attributed to several factors associated with plastic pollution. The physical presence of plastic bottles can shade the benthos, reducing light penetration essential for photosynthesis (Fig. 07 shows a decrease in light intensity from 1127 to 1022 Lux). Furthermore, plastics can leach harmful chemical additives or act as vectors for other pollutants (Teuten et al., 2009 and Rochman et al., 2013), creating a toxic environment for sensitive algal species.

Primary Consumers (Aquatic Insects): The dominant primary consumer, *Lathocerus americanus*, was observed to have emigrated from the polluted site. The study notes that these white flies were found approximately 200 meters away, near a small waterfall with no plastic bottles. This displacement suggests that the presence of plastic pollution rendered the original habitat unsuitable. The reasons for this are likely twofold: the loss of their algal food source and the direct toxicological effects of plastic leachates, which are known to cause sub-lethal effects and avoidance behavior in aquatic insects (Imhof et al., 2013).

Secondary Consumer (Fish): The most compelling evidence of ecological disruption was the complete absence of *Schizothorax plagiostomus* from the polluted lentic ecosystem in 2020. The study reported that no individuals were collected in the picnic spot area, and they were only found in deeper, faster-flowing sections of the main Swat River, approximately 400 meters away. This is a stark contrast to the 2018 survey where the species was readily collected using a fishery net. This migration is a clear behavioral response to avoid the polluted area. Fish often emigrate from areas with degraded water quality, reduced food availability (due to the loss of algae and insects), and the stress of chemical contaminants. The quantitative fish collection data (Figs. 09 & 10) further supports this trend, showing a drastic decline in catch rates at all times of the day in 2020 compared to 2018.

Table (4): Summary of observed changes in biotic communities between 2018 and 2020.

Parameter	**Natural Habitat (Before Pollutant, 2018)**	**Natural Habitat (After Pollutant, 2020)**
Zygnema cruciatum	Dominant, forming blooms	Totally disturbed, no regular colonies
Navicula subtilissima	Present on rocks	Presence and dominance diminished
Lathocerus americanus	Dominant in the area	Emigrated ~200m away to a non-polluted site
Schizothorax plagiostomus	Readily collected in the lentic ecosystem	Absent from the area, found ~400m away in deep, fast water

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

Analysis of Abiotic Factors

While the primary focus was on biotic communities, changes in abiotic factors were also recorded (Fig. 07). While parameters like pH, electrical conductivity, and salinity remained relatively stable, notable changes were observed in temperature, depth, and light intensity. The temperature range shifted from 9-12°C to a higher minimum of 13°C, which could be a result of reduced shading from algal cover and changes in water flow. The maximum depth increased from 3-4 feet to 8-11 feet, potentially altering the habitat structure. Light intensity also decreased, likely due to the accumulation of plastic debris on the water surface or bottom, further impacting primary production.

Discussion of Findings

The findings of this study provide a clear, multi-trophic level case study of the negative impacts of plastic pollution on a freshwater ecosystem. The observed emigration of insects and fish, coupled with the collapse of the algal community, demonstrates a fundamental disruption to the food web. The initial observation from the abstract, regarding the count of heavy metals increasing from 0% to 13% in the winter of 2019-2020, is a critical piece of evidence, even though its methodology is not detailed in the current section. This increase strongly suggests that plastics, by acting as a vector for heavy metals or through the leaching of their own chemical components, are contributing to chemical contamination. This aligns with the findings of Rochman et al. (2013), who demonstrated that plastic can transfer hazardous chemicals to fish.

The study's results confirm the growing body of evidence that freshwater ecosystems are not immune to the threats of plastic pollution, a concern previously highlighted by Wagner et al. (2014) and Eerkes-Medrano et al. (2015). The specific and localized impact observed at a picnic spot underscores the role of human recreational activity as a direct source of pollution, as visitors discard plastic bottles. This on-the-ground observation validates the concerns raised by Faure et al. (2015) about human activity near water resources.

Furthermore, the study illustrates the cascading effects of such pollution. The primary impact of plastic bottles—physical smothering, chemical leaching, and light reduction—first affected the base of the food web (the producers). This, in turn, led to a loss of habitat and food for primary consumers (insects), which ultimately forced the secondary consumers (fish) to migrate to find suitable conditions. This cascading disruption highlights how plastic pollution threatens not only individual species but also the integrity and stability of the entire aquatic ecosystem.

The significant decline in fish catch rates from an average of 6/net at 4:00 AM in 2018 to 1.5/net in 2020, and to zero catches during daytime hours, has severe implications for local communities. As noted in the introduction, the Swat River is a prime source for fishing, irrigation, and drinking water (Shah et al., 2016). The degradation of this resource directly threatens the livelihoods and well-being of the people dependent on it. The almost negligible decomposition rate of plastic bottles mentioned in the abstract means that without intervention, this pollution and its associated impacts will persist for decades, potentially creating a permanent "technofossil" record of this disturbance (Zalasiewicz et al., 2016).

Conclusion

The results of this study provide clear evidence that plastic bottle pollution is causing significant and negative changes to the freshwater biota of the Swat Valley. The observed disruption of algal blooms, emigration of aquatic insects and fish, and changes in water quality parameters demonstrate a severe impact across trophic levels. The study reinforces the urgent need for regulatory authorities to address this issue. Preventive measures, such as enforcing bans on single-use plastics in protected picnic areas and installing proper waste management infrastructure, are critical. Remedial measures, including clean-up drives, are also necessary to restore the health of these beautiful and ecologically important uphill streams and lakes. Future research should focus on quantifying the heavy metal concentrations directly linked to the plastics and further investigating the sub-lethal physiological effects on the affected species.

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

References

Biginagwa, F. J., Mayoma, B. S., Shashoua, Y., Syberg, K., & Khan, F. R. (2016). First evidence of microplastics in the African Great Lakes: Recovery from Lake Victoria Nile perch and Nile tilapia. *Journal of Great Lakes Research*, 42 (1), 146–149. https://doi.org/10.1016/j.jglr.2015.10.012

Blettler, M. C. M., Abrial, E., Khan, F. R., Sivri, N., & Espinola, L. A. (2018). Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. *Water Research*, 143, 416–424. https://doi.org/10.1016/j.watres.2018.06.037

Blettler, M. C. M., Ulla, M. A., Rabuffetti, A. P., & Garello, N. (2017). Plastic pollution in freshwater ecosystems: Macro-, meso-, and microplastic debris in a floodplain lake. *Environmental Monitoring and Assessment*, 189 (11), Article 581. https://doi.org/10.1007/s10661-017-6305-8

Browne, M. A., Dissanayake, A., Galloway, T. S., Lowe, D. M., & Thompson, R. C. (2008). Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environmental Science & Technology*, 42 (13), 5026–5031. https://doi.org/10.1021/es800249a

Correia Prata, J. (2018). Microplastics in wastewater: State of the knowledge on sources, fate and solutions. *Marine Pollution Bulletin*, 129 (1), 262–265. https://doi.org/10.1016/j.marpolbul.2018.02.046

Eerkes-Medrano, D., Thompson, R. C., & Aldridge, D. C. (2015). Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research*, 75 , 63–82. https://doi.org/10.1016/j.watres.2015.02.012

Faure, F., Demars, C., Wieser, O., Kunz, M., & de Alencastro, L. F. (2015). Plastic pollution in Swiss surface waters: Nature and concentrations, interaction with pollutants. *Environmental Chemistry*, 12 (5), 582–591. https://doi.org/10.1071/EN14218

Fischer, E. K., Paglialonga, L., Czech, E., & Tamminga, M. (2016). Microplastic pollution in lakes and lake shoreline sediments—A case study on Lake Bolsena and Lake Chiusi (central Italy). *Environmental Pollution*, 213 , 648–657. https://doi.org/10.1016/j.envpol.2016.03.012

Heckel, J. J. (1838). *Fische aus Caschmir gesammelt und herausgegeben von Carl Freiherrn von Hügel, beschrieben von J. J. Heckel*. Gedruckt bei den P.P. Mechitaristen.

Imhof, H. K., Ivleva, N. P., Schmid, J., Niessner, R., & Laforsch, C. (2013). Contamination of beach sediments of a subalpine lake with microplastic particles. *Current Biology*, 23 (19), R867–R868. https://doi.org/10.1016/j.cub.2013.09.001

Klein, S., Worch, E., & Knepper, T. P. (2015). Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. *Environmental Science & Technology*, 49 (10), 6070–6076. https://doi.org/10.1021/acs.est.5b00492

Lal, B. B. (2005). Aryan invasion of India: Perpetuation of a myth. In E. F. Bryant & L. L. Patton (Eds.), *The Indo-Aryan controversy: Evidence and inference in Indian history* (pp. 50–74). Routledge.

Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M., Glas, M., & Schludermann, E. (2014). The Danube so colourful: A potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. *Environmental Pollution*, 188 , 177–181. https://doi.org/10.1016/j.envpol.2014.02.006

Leidy, J. (1853). *A flora and fauna within living animals*. Smithsonian Institution.

Mintenig, S. M., Int-Veen, I., Löder, M. G. J., Primpke, S., & Gerdts, G. (2017). Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. *Water Research*, 108 , 365–372. https://doi.org/10.1016/j.watres.2016.11.015

Pazos, R. S., Maiztegui, T., Colautti, D. C., Paracampo, A. H., & Gómez, N. (2017). Microplastics in gut contents of coastal freshwater fish from Río de la Plata estuary. *Marine Pollution Bulletin*, 122 (1–2), 85–90. https://doi.org/10.1016/j.marpolbul.2017.06.007

Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., & Li, D. (2017). Microplastics in sediments of the Changjiang Estuary, China. *Environmental Pollution*, 225 , 283–290. https://doi.org/10.1016/j.envpol.2016.12.064

Prescott, G. W. (1954). *How to know the fresh-water algae: An illustrated key for identifying the more common fresh-water algae to genus, with hundreds of species named pictured and with numerous aids for their study*. W. C. Brown Co.

Reid, G. K. (1967). *Pond life: A guide to common plants and animals of North American ponds and lakes* (S. D. Kaicher & T. Dolan, Illus.). Golden Press.

Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports*, 3 , Article 3263. https://doi.org/10.1038/srep03263

Rosenkranz, P., Chaudhry, Q., Stone, V., & Fernandes, T. F. (2009). A comparison of nanoparticle and fine particle uptake by *Daphnia magna*. *Environmental Toxicology and Chemistry*, 28 (10), 2142–2149. https://doi.org/10.1897/08-559.1

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

RICOS BIOLOGY Journal
2026, Vol. 4, No. 3, 26-35.
doi: https://doi.org/10.33687/ricosbiol.04.03.110

Sanchez, W., Bender, C., & Porcher, J. M. (2014). Wild gudgeons (*Gobio gobio*) from French rivers are contaminated by microplastics: Preliminary study and first evidence. *Environmental Research*, 128 , 98–100. https://doi.org/10.1016/j.envres.2013.11.004

Schwarzenbach, R. P., Egli, T., Hofstetter, T. B., von Gunten, U., & Wehrli, B. (2010). Global water pollution and human health. *Annual Review of Environment and Resources*, 35 , 109–136. https://doi.org/10.1146/annurev-environ-100809-125342

Seamer, D. G. (2017). *A beginners guide to freshwater microscopic life*. David Seamer.

Shah, S. A., Shah, N. A., Ullah, S., Alam, M. M., Badshah, H., Ullah, S., & Mumtaz, A. S. (2016). Documenting the indigenous knowledge on medicinal flora from communities residing near Swat River (Suvastu) and in high mountainous areas in Swat-Pakistan. *Journal of Ethnopharmacology*, 182, 67–79. https://doi.org/10.1016/j.jep.2016.01.042

Shaw, D. K., & Sahni, P. (2014). Plastic to oil. *Journal of Mechanical and Civil Engineering*, 11 (3), 46–48. https://doi.org/10.9790/1684-11344648

Sigler, M. (2014). The effects of plastic pollution on aquatic wildlife: Current situations and future solutions. *Water, Air, & Soil Pollution*, 225 (11), Article 2184. https://doi.org/10.1007/s11270-014-2184-6

Sutherland, W. J., Clout, M., Côté, I. M., Daszak, P., Depledge, M. H., Fellman, L., Fleishman, E., Garthwaite, R., Gibbons, D. W., De Lurio, J., Impey, A. J., Lickorish, F., Lindenmayer, D., Madgwick, J., Margerison, C., Maynard, T., Peck, L. S., Pretty, J., Prior, S., … Watkinson, A. R. (2010). A horizon scan of global conservation issues for 2010. *Trends in Ecology & Evolution*, 25 (1), 1–7. https://doi.org/10.1016/j.tree.2009.10.003

Teuten, E. L., Saquing, J. M., Knappe, D. R. U., Barlaz, M. A., Jonsson, S., Björn, A., Rowland, S. J., Thompson, R. C., Galloway, T. S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P. H., Tana, T. S., Prudente, M., Boonyatumanond, R., Zakaria, M. P., Akkhavong, K., Takada, H. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364 (1526), 2027–2045. https://doi.org/10.1098/rstb.2008.0284

UNEP. (2014). *United Nations Environment Programme year book 2014: Emerging issues in our global environment*. United Nations Environment Programme.

Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., Fries, E., Grosbois, C., Klasmeier, J., Marti, T., Rodriguez-Mozaz, S., Urbatzka, R., Vethaak, A. D., Winther-Nielsen, M., & Reifferscheid, G. (2014). Microplastics in freshwater ecosystems: What we know and what we need to know. *Environmental Sciences Europe*, 26 , Article 12. https://doi.org/10.1186/s12302-014-0012-7

Zalasiewicz, J., Waters, C. N., Ivar do Sul, J. A., Corcoran, P. L., Barnosky, A. D., Cearreta, A., Edgeworth, M., Gałuszka, A., Jeandel, C., Leinfelder, R., McNeill, J. R., Steffen, W., Summerhayes, C., Wagreich, M., Williams, M., Wolfe, A. P., & Yonan, Y. (2016). The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. *Anthropocene*, 13 , 4–17. https://doi.org/10.1016/j.ancene.2016.01.002

Copyright: Copyrights retained to the Authors. Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/ by/4.0/), which permits unrestricted use, distribution, andreproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http:// creativecommons.org/public domain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

Corresponding author:*Shujaul Mulk Khan*
shujaqau@gmail.com
Ricos Biology Journal ISSN 2959-3751(*E*), 2959-3743(P)
www.https://ricosbiology.net
contact info@ricosbiology.net

© 2026 Copyright by the Author

Scilit