BÖLÜM 4

ELEKTROAKTİF BAKTERİLERİN ENFEKSİYON HASTALIKLARININ TEDAVİSİNDE KULLANIMI

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GİRİŞ

Elektroaktif bakteriler (EAB), elektriksel aktiviteleri kullanarak enerji üretebilen ve bu özellikleri sayesinde çeşitli biyoteknolojik uygulamalarda kullanılmaktadır. EAB'ler son yıllarda antibiyotik direncinin artması ve mevcut tedavi yöntemlerinin yetersiz kalması nedeniyle büyük ilgi görmektedir. Bu bakterilerin enfeksiyon hastalıklarının tedavisinde kullanımı, antibiyotiklere dirençli patojenlerin kontrol altına alınmasında yeni bir yaklaşım sunmaktadır (1). Antibiyotik direnci, dünya genelinde sağlık sistemlerini tehdit eden önemli bir sorun haline gelmiştir. Özellikle karbapenem dirençli bakteriler, tedavi seçeneklerini sınırlandırmakta ve ciddi enfeksiyonlara yol açmaktadır (2). Bu bağlamda, EAB'lerin kullanımı, antibiyotiklerin etkisiz kaldığı durumlarda alternatif bir tedavi yöntemi olarak öne çıkmaktadır. Örneğin, EAB'ler, biyofilm oluşumunu engelleyerek veya mevcut biyofilm yapılarının parçalanmasına yardımcı olarak enfeksiyonların tedavisinde etkili olabilmektedir (1).

EAB'lerin enfeksiyon hastalıkların tedavisindeki potansiyeli, özellikle mikrobiyal yakıt hücreleri (MYH) gibi uygulamalarda vurgulanmaktadır. Bu sistemler, bakterilerin elektrik üretme kabiliyetinden yararlanarak enfeksiyon bölgelerine enerji sağlamak ve böylece antibakteriyel aktiviteyi arttırmak için kullanılabilir. EAB'ler, antibiyotiğe dirençli patojenleri doğrudan etkileme ve bu bakterilerin virülans faktörlerini hedefleme konusunda umut vaat etmektedir ki bu, artan antibiyotik direnci bağlamında çok önemlidir. Ayrıca, EAB'lerin çeşitli patojenlerle etkileşime girme ve virülans faktörlerini modüle etme yeteneği, özellikle dirençli

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daha fazla araştırma ve geliştirme gerektirmektedir. Özellikle, bu bakterilerin mekanizmalarının daha iyi anlaşılması, yeni tedavi yöntemlerinin geliştirilmesine olanak sağlayacaktır. Ayrıca, EAB'lerin kullanımıyla ilgili klinik çalışmaların artırılması, bu alandaki bilgilerin derinleşmesine katkıda bulunacaktır (60).

SONUÇ

EAB'lerin enfeksiyon hastalıkların tedavisine entegrasyonu, elektron transfer yeteneklerinden yararlanan çok yönlü bir yaklaşım sunmaktadır. Biyoalgılama, biyoremediasyon ve doğrudan antimikrobiyal aktivite yoluyla, bu mikroorganizmalar halk sağlığını iyileştirmek için önemli bir potansiyele sahiptir. Bu alanda devam eden araştırma ve geliştirmeler, mevcut zorlukların üstesinden gelmek ve enfeksiyon hastalıklarla mücadelede EAB'lerin tam potansiyelini gerçekleştirecektir. Antibiyotik direncinin artması ve mevcut tedavi yöntemlerinin yetersiz kalması, bu bakterilerin potansiyelinin daha da önem kazanmasına yol açmaktadır. Ancak, bu alandaki araştırmaların devam etmesi ve EAB'lerin klinik uygulamalardaki etkinliğinin daha fazla incelenmesi gerekmektedir.

Sonuç olarak, EAB'lerin enfeksiyon hastalıklarının tedavisinde kullanımı, antibiyotik direncinin arttığı günümüzde umut verici bir alternatif olarak değerlendirilmektedir. Bu bakterilerin, mevcut tedavi yöntemlerine ek olarak, enfeksiyonların kontrol altına alınmasında ve tedavi süreçlerinde önemli bir rol oynaması beklenmektedir. Ancak, bu alandaki araştırmaların devam etmesi ve EAB'lerin klinik uygulamalardaki etkinliğinin daha fazla incelenmesi gerekmektedir.

KAYNAKLAR

1. Garbini GL, Caracciolo A., Grenni P. Electroactive Bacteria in Natural Ecosystems and Their Applications in Microbial Fuel Cells for Bioremediation: A Review. *Microorganisms*. 2023;11(5): 1255. doi: 10.3390/microorganisms11051255.
2. Koçak C, Hazırolan G. Colistin resitance in carbapenem resistant k. pneumoniae clinical isolates. *Türk Mikrobiyoloji Cemiyeti Dergisi*. 2019;49(1): 17-23. https://doi.org/10.5222/tmcd.2019.017.
3. Cao B, Zang Y, Xie B, et al. Visualization isolation of electrochemically active bacteria by using a gelled electrode-based electrochemical plate. *Acs Es&t Engineering*. 2024;4(10): 2533-2541. https://doi.org/10.1021/acsestengg.4c00308.
4. Leung K, Gerson J, Emmons N, et al. A tight squeeze: geometric effects on the performance of three-electrode electrochemical-aptamer based sensors in constrained, in vivo placements. *The Analyst*. 2023;148(7): 1562-1569. https://doi.org/10.1039/d2an02096c.
5. Aygül A. The importance of efflux systems in antibiotic resistance and efflux pump inhibitors in the management of resistance. *Mikrobiyoloji Bulteni*. 2015;49(2): 278-291. https://doi.org/10.5578/mb.8964.
6. Zhao F, Chen Y, Zhang S, et al. Three-dimensional carbon monolith coated by nano-tio2 for anode enhancement in microbial fuel cells. *International Journal of Environmental Research and Public Health*. 2023;20(4): 3437. https://doi.org/10.3390/ijerph20043437.
7. Choi S. Electrogenic bacteria promise new opportunities for powering, sensing, and synthesizing. *Small*. 2022;18(18): e2107902. https://doi.org/10.1002/smll.202107902.

8. Liang Q, Yamashita T, Matsuura N, et al. Community structure analyses of anodic biofilms in a bioelectrochemical system combined with an aerobic reactor. *Energies*. 2019;12(19): 3643. https://doi.org/10.3390/en12193643.
9. Tahernia M, Plotkin-Kaye E, Mohammadifar M, et al. Characterization of electrogenic gut bacteria. *Acs Omega*. 2020;5(45): 29439-29446. https://doi.org/10.1021/acsomega.0c04362.
10. Zarlashat Y, Mushtaq H, Shah S. Exploring microbial electroactivity: from skin microbiota to cable bacteria in microbial fuel cells. *Advances in biotechnology and microbiology*. 2024;18(1): 555979 https://doi.org/10.19080/aibm.2024.18.555979.
11. Ramírez- Moreno M, Berenguer R, Ortiz JM., et al. Study of the influence of nanoscale porosity on the microbial electroactivity between expanded graphite electrodes and geobacter sulfurreducens biofilms. *Microbial Biotechnology*. 2023;17(1): e14357. https://doi.org/10.1111/1751-7915.14357.
12. Li S, Sheng G, Cheng Y,et al. Redox properties of extracellular polymeric substances (eps) from electroactive bacteria. *Scientific Reports*. 2016;6(1): 39098. https://doi.org/10.1038/srep39098.
13. Li J, Liu F, Yang C, et al. Inhibition effect of polyvinyl chloride on ferrihydrite reduction and electrochemical activities of geobacter metallireducens. *Journal of Basic Microbiology.* 2019;60(1): 37-46. https://doi.org/10.1002/jobm.201900415.
14. Umar M, Rafatullah M, Khan M, et al. Power generation and toluene bioremediation through single chamber benthic microbial fuel cell fed with sugarcane waste as a substrate. *International Journal of Energy Research.* 2022;46(7): 8687-8699. https://doi.org/10.1002/er.7747.
15. Xiao L, Li J, Lichtfouse E, et al. Augmentation of chloramphenicol degradation by geobacter-based biocatalysis and electric field. *Journal of Hazardous Materials*. 2021;410: 124977. https://doi.org/10.1016/j.jhazmat.2020.124977.
16. Jugnia L, Manno D, Hendry M, et al. Removal of heavy metals in a flow- through vertical microbial electrolysis cell. *The Canadian Journal of Chemical Engineering*. 2019;97(10): 2608-2616. https://doi.org/10.1002/cjce.23568.
17. Najjarzadeh N, Krige A, Pamidi T, et al. Numerical modeling and verification of a sonobioreactor and its application on two model microorganisms. *Plos One*. 2020;15(3): e0229738. https://doi.org/10.1371/journal.pone.0229738.
18. Abbas Z, Yousra Bibi H, Khalid U, et al. (2025). Enhanced methane and energy generation from sewage water using microbial fuel cells with paddy field soil substrate. *Energy Exploration & Exploitation*. 2025;43(1): 29-46. https://doi.org/10.1177/01445987241287876.
19. Fernandes TM, Morgado L, Turner DL, et al. Protein Engineering of Electron Transfer Components from Electroactive Geobacter Bacteria. *Antioxidants*. 2021;10(6): 844. doi:10.3390/antiox10060844.
20. Bjerg J, Boschker H, Larsen S, et al. Long-distance electron transport in individual, living cable bacteria. *Proceedings of the National Academy of Sciences.* 2018;115(22): 5786-5791. https://doi.org/10.1073/pnas.1800367115.
21. Wang LC, Chen HK, Wang WJ, et al. Boosting Upconversion Efficiency in Optically Inert Shelled Structures with Electroactive Membrane through Electron Donation. *Adv Mater*. 2024;36(30): e2404120. doi: 10.1002/adma.202404120.
22. Costa N, Hermann B, Fourmond V, et al. How thermophilic gram-positive organisms perform extracellular electron transfer: characterization of the cell surface terminal reductase ocwa. *Mbio*. 2019;10(4): e01210-19. https://doi.org/10.1128/mbio.01210-19.
23. Walker D, Nevin K, Holmes D, et al. Syntrophus conductive pili demonstrate that common hydrogen-donating syntrophs can have a direct electron transfer option. *The Isme Journal*. 2020;14(3): 837-846. https://doi.org/10.1038/s41396-019-0575-9.
24. Aiyer K, Mukherjee D, Doyle LE. A Weak Electricigen-Based Bioelectrochemical Sensor for Real-Time Monitoring of Chemical Pollutants in Water. *ACS Applied Bio Materials*, 2023;6(10): 4105-4110. https://doi.org/10.1021/acsabm.3c00601.
25. Costa NL, Clarke TA, Philipp LA, et al. Electron transfer process in microbial electrochemical technologies: the role of cell-surface exposed conductive proteins. *Bioresource Technology*.

2018;255, 308-317. https://doi.org/10.1016/j.biortech.2018.01.133.
26. Wang H, Jing X, Feng K, et al. In Situ Tuning the Structure of Geobacter Biofilm for Bioelectricity Enhancement. *Environmental Science & Technology Letters.* 2024;11(2): 106-113. doi:10.1021/acs.estlett.3c00783.
27. Yin Y, Liu X, Nealson K, et al. Dissecting the structural and conductive functions of nanowires in geobacter sulfurreducens electroactive biofilms. *Mbio*. 2022;13(1):e0382221. https://doi.org/10.1128/mbio.03822-21.
28. Angelaalincy M, Krishnaraj R, Shakambari G, et al. Biofilm engineering approaches for improving the performance of microbial fuel cells and bioelectrochemical systems. *Frontiers in Energy Research. 2018;6: 63.* https://doi.org/10.3389/fenrg.2018.00063.
29. Gaffney E, Dantanarayana A, Simoska O. Investigating the electroactivity of salinivibrio sp. eagsl, through electroanalytical techniques and genomic insights. *Journal of the Electrochemical Society.* 2022;169(2): 025501. https://doi.org/10.1149/1945-7111/ac4fee.
30. Hu Y, Wang Y, Han X, et al.. Biofilm Biology and Engineering of Geobacter and Shewanella spp. for Energy Applications. *Front Bioeng Biotechnol.* 2021;9: 786416. doi: 10.3389/fbioe.2021.786416.
31. Ramírez-Vargas C, Prado A, Arias C, et al. Microbial electrochemical technologies for wastewater treatment: principles and evolution from microbial fuel cells to bioelectrochemical-based constructed wetlands. *Water.* 2018;10(9): 1128. https://doi.org/10.3390/w10091128.
32. Zhou Y, Simeng Z, Yin L, et al. Development of a novel membrane- less microbial fuel cell (mlmfc) with a sandwiched nitrifying chamber for efficient wastewater treatment. *Electroanalysis*. 2018;30(9): 2145-2152. https://doi.org/10.1002/elan.201800232.
33. An Z, Feng Q, Zhao R, et al. Bioelectrochemical methane production from food waste in anaerobic digestion using a carbon-modified copper foam electrode. *Processes*. 2020;8(4): 416. https://doi.org/10.3390/pr8040416.
34. Lichtervelde A, Heijne A, Hamelers H, et al. Theory of ion and electron transport coupled with biochemical conversions in an electroactive biofilm. *Physical Review Applied*. 2019;12(1): 014018. https://doi.org/10.1103/physrevapplied.12.014018.
35. Massaglia G, Quaglio M. 3D composite pdms/mwcnts aerogel as high-performing anodes in microbial fuel cells. *Nanomaterials.* 2022;12(23): 4335. https://doi.org/10.3390/nano12234335.
36. Heijne A, Pereira M, Pereira J, et al. Electron storage in electroactive biofilms. *Trends in Biotechnology.* 2021;39(1): 34-42. https://doi.org/10.1016/j.tibtech.2020.06.006.
37. Lin WQ, Cheng ZH, Wu QZ, et al. Efficient Enhancement of Extracellular Electron Transfer in Shewanella oneidensis MR-1 via CRISPR-Mediated Transposase Technology. *ACS Synth Biol*. 2024;13(6): 1941-1951. doi: 10.1021/acssynbio.4c00240.
38. Light S, Su L, Rivera- Lugo R, et al. A flavin-based extracellular electron transfer mechanism in diverse gram-positive bacteria. *Nature*. 2018;562(7725): 140-144. https://doi.org/10.1038/s41586-018-0498-z.
39. Stöckl M, Teubner N, Holtmann D, et al. Extracellular polymeric substances from geobacter sulfurreducens biofilms in microbial fuel cells. *Acs Applied Materials & Interfaces*. 2019;11(9): 8961-8968. https://doi.org/10.1021/acsami.8b14340.
40. Zhang X, Liu Y, Zhou Q, et al. Exogenous electroactive microbes regulate soil geochemical properties and microbial communities by enhancing the reduction and transformation of fe(iii) minerals. *Environmental Science & Technology.* 2023;57(20): 7743-7752. https://doi.org/10.1021/acs.est.3c00407.
41. Zhu N, Zhang X, Yang S, et al. Photic biofilms mediated distant nitrate reduction at the soil–water interface of paddy fields. *Acs Earth and Space Chemistry*. 2021;5(5): 1163-1171. https://doi.org/10.1021/acsearthspacechem.1c00040.
42. Ganzorig B, Zayabaatar E, Pham M, et al. Lactobacillus plantarum generate electricity through flavin mononucleotide-mediated extracellular electron transfer to upregulate epithelial type i collagen expression and. thereby promote microbial adhesion to intestine. *Biomedicines.* 2023;11(3): 677. https://doi.org/10.3390/biomedicines11030677.

43. Kim Y, Mosteller M, Subramanian S, et al. An optical microfluidic platform for spatiotemporal biofilm treatment monitoring. *Journal of Micromechanics and Microengineering*, 2015;26(1): 015013. https://doi.org/10.1088/0960-1317/26/1/015013.
44. Pasternak G, Greenman J, Ieropoulos I. Removal of hepatitis b virus surface hbsag and core hbcag antigens using microbial fuel cells producing electricity from human urine. *Scientific Reports*. 2019;9(1): 11787 https://doi.org/10.1038/s41598-019-481.
45. Yuan H, Miller J, Abu-Reesh I, et al. Effects of electron acceptors on removal of antibiotic resistant escherichia coli, resistance genes and class 1 integrons under anaerobic conditions. *The Science of the Total Environment.* 2016;569-570: 1587-1594. https://doi.org/10.1016/j.scitotenv.2016.07.002.
46. Machado M, Zamani M, Daniel S, et al. Bioelectrochemical platforms to study and detect emerging pathogens. *Mrs Bulletin,* 2021;46(9): 840-846. https://doi.org/10.1557/s43577-021-00172-7.
47. Salomoni R, Léo P, Montemor A, et al. Antibacterial effect of silver nanoparticles in Pseudomonas aeruginosa. *Nanotechnology Science and Applications*. 2017;10: 115-121. https://doi.org/10.2147/nsa.s133415.
48. Son J, Koo D, Han S, et al. Bioelectric dressing on skin graft donor sites: a pilot clinical trial. *Journal of Wound Management and Research.* 2022;18(2): 92-97. https://doi.org/10.22467/jwmr.2022.01942.
49. Lin X, Liu P, Yan J, et al. Dual synthetic receptor-based sandwich electrochemical sensor for highly selective and ultrasensitive detection of pathogenic bacteria at the single-cell level. *Analytical Chemistry*. 2023;95(13): 5561-5567. https://doi.org/10.1021/acs.analchem.2c04657.
50. Xing F, Duan L, Zhang H, et al. Research on the application and mechanisms of electroactive microorganisms in toxicants monitoring: a review. *Toxics*. 2024;12(3): 173. https://doi.org/10.3390/toxics12030173.
51. Franca M, Matturro B, Crognale S, et al. Microbiome composition and dynamics of a reductive/oxidative bioelectrochemical system for perchloroethylene removal: effect of the feeding composition. *Frontiers in Microbiology.* 2022;13: 951911. doi: 10.3389/fmicb.2022.951911.
52. Korth B, Maskow T, Picioreanu C, et al. The microbial electrochemical peltier heat: an energetic burden and engineering chance for primary microbial electrochemical technologies. *Energy & Environmental Science.* 2016;9(8): 2539-2544. https://doi.org/10.1039/c6ee01428c.
53. Zhou X, Zhang X, Peng Y, et al. Electroactive microorganisms in advanced energy technologies. *Molecules.* 2023;28(11): 4372. https://doi.org/10.3390/molecules28114372.
54. Borole A, Reguera G, Ringeisen B, et al. Electroactive biofilms: current status and future research needs. *Energy & Environmental Science.* 2011;4(12): 4813-4834. https://doi.org/10.1039/c1ee02511b.
55. Bonne R, Wouters K, Lustermans J, et al. Biomaterials and electroactive bacteria for biodegradable electronics. *Frontiers in Microbiology.* 2022;13: 906363. https://doi.org/10.3389/fmicb.2022.906363.
56. Jin X, Yang N, Xu D, et al. Insight into a single-chamber air-cathode microbial fuel cell for nitrate removal and ecological roles. *Frontiers in Bioengineering and Biotechnology*. 2024;12: 1397294. https://doi.org/10.3389/fbioe.2024.1397294.
57. Sydow A, Krieg T, Mayer F, et al. Electroactive bacteria—molecular mechanisms and genetic tools. *Applied Microbiology and Biotechnology.* 2014;98(20): 8481-8495. https://doi.org/10.1007/s00253-014-6005-z.
58. Zhuang X, Wang S, Wu S. Electron transfer in the biogeochemical sulfur cycle. *Life*. 2024;14(5): 591. https://doi.org/10.3390/life14050591.
59. Yee M, Deutzmann J, Spormann A, et al. Cultivating electroactive microbes—from field to bench. *Nanotechnology*. 2020;31(17): 174003. https://doi.org/10.1088/1361-6528/ab6ab5.
60. Balasubramaniam A, Adi P, Thi T, et al. Skin bacteria mediate glycerol fermentation to produce electricity and resist uv-b. *Microorganisms*. 2020;8(7): 1092. https://doi.org/10.3390/microorganisms8071092.