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Review Article

Vitaminlerin ve Metallerin Çift Yönlü Etkileri: Sağlık, Mutajenite ve Antimutajenite Üzerine Bir İnceleme

Eda DELİK [1], Burcu Emine TEFON-ÖZTÜRK [1], Bülent KAYA [1*]

Article Info

**Corresponding author*:

e-mail: bkaya@akdeniz.edu.tr

Institution: [1] Akdeniz Üniversitesi, Fen Fakültesi, Biyoloji Bölümü

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ÖZET

Ağır metaller ve vitaminler insan sağlığı üzerinde önemli etkilere sahip maddelerdir. Çevresel ve endüstriyel kaynaklardan dolayı ağır metallere maruziyet toksik etkilere yol açarken, vitaminler genellikle vücut fonksiyonlarını destekleyen esansiyel bileşenler olarak bilinmektedir. Ancak her iki grup da insan sağlığı açısından doza bağlı olarak zararlı veya yararlı olabilmektedir. İkisinin de ortak noktalarından biri, eser miktarda insan vücudu için gerekli olmalarıdır. Ayrıca hem ağır metaller hem de vitaminler metabolizmanın düzgün yürüyebilmesi için genellikle vücuda dışarıdan alınmaları gereken maddelerdir. Bu derlemede ağır metallerin ve vitaminlerin toksik ve antitoksik etkileri ele alınmıştır. Ayrıca bu maddelerin insan sağlığı üzerindeki etkileri maruz kalınan dozlarla ilişkilendirilerek hem zararlı hem de yararlı yönleri üzerinde durulmuştur. Sağlık için önemli bazı metallere ve vitamin gruplarına değinilerek, yüksek dozların potansiyel toksisite yaratabileceği vurgulanmıştır. Sonuç olarak bu derleme bireylerin sağlığını koruma stratejileri geliştirmelerine ve sağlık profesyonellerinin maruziyet risklerini etkili bir şekilde yönetmelerine yönelik önemli bulgular sunmayı amaçlamıştır.

The Dual Effects of Vitamins and Metals: A Review on Health, Mutagenicity, and Antimutagenicity

ABSTRACT

Heavy metals and vitamins are substances that have significant impacts on human health. While exposure to heavy metals from environmental and industrial sources leads to toxic effects, vitamins are generally recognised as essential components that support body functions. However, depending on the dose, both groups can be harmful or beneficial to human health. One thing they have in common is that they are both required in trace amounts by the human body. Both heavy metals and vitamins are substances that generally need to be taken into the body from external sources for the metabolism to function properly. This review addresses the toxic and antitoxic effects of heavy metals and vitamins. It also examines the effects of these substances on human health depending on the dose, emphasising both their harmful and beneficial aspects. Important metals and groups of vitamins for health are discussed, emphasizing that high doses can potentially lead to toxicity. As a result, this review presents significant

findings to help individuals develop strategies to protect their health and health professionals to manage exposure risks effectively.

1. GİRİŞ

Vitaminler ve metaller biyolojik sistemlerde metabolizma için önemli roller oynayan iki farklı molekül grubudur. Vitaminler, organizmanın büyüme, gelişme ve metabolik süreçlerinde kritik öneme sahip organik bileşiklerdir. İnsan vücudu bu bileşiklerin birçoğunu sentezleyemediği için besin veya takviyelerle dış kaynaklardan almak zorundadır. Vitaminlerin antioksidan özellikleri hücre içi oksidatif stresin azaltılmasında ve DNA hasarının önlenmesinde önemli rol oynamaktadır. Ancak bazı vitaminlerin aşırı alımı toksik etkilere yol açarak potansiyel mutajenik etkilere neden olabilmektedir [1], [2], [3]. Ağır metaller ise genellikle çevresel kirleticiler olarak bilinmesine rağmen bazıları eser elementler olarak vücutta hayati fonksiyonlar üstlenir ve belirli dozlarda antimutajenik özellik sergilerler [4]. Bununla birlikte, yüksek konsantrasyonlarda DNA'ya zarar verebilir ve mutajenik etkiler gösterebilirler [5]. Ayrıca daha önce yapılan çalışmalarda vitaminlerin metaller ile birlikte maruziyetinde olası toksik ve antitoksik etkiler gösterebildiği ve birbirleri üzerinde modülatör etki gösterebildiği de bildirilmiştir. Örneğin Kaya vd. [6] askorbik asidin (Vitamin C) farklı ağır metallerin ve kimyasalların genotoksik etkileri üzerindeki modülatör etkisinin değişken olduğunu bildirmiştir. Askorbik asit potasyum dikromatın ($K_2Cr_2O_7$) genotoksisitesini azaltırken 4-nitrokinolin-1-oksit (4-NQO) ile hiçbir koruyucu etki göstermemiş ve kobalt klorürün ($CoCl_2$) genotoksisitesini artırmıştır. Bu bulgular bu tür maddelerin birlikte kullanımı durumunda dikkatli olunması gerektiğini vurgulamaktadır.

Bu makalede vitaminlerin ve ağır metallerin insan vücudundaki biyolojik rollerine ve toksik etkilerine odaklanılmıştır. Vitaminler genellikle vücut sağlığı için gerekli ve yararlı olarak bilinirken yüksek konsantrasyonlarda toksik etkileri olabileceği göz ardı edilmemelidir. Öte yandan ağır metaller genellikle zararlı olarak kabul edilmekle birlikte, bazıları iz elementler olarak hayati biyolojik işlevlere sahiptir. Bu derleme vitaminlerin ve belirli ağır metallerin toksik/antitoksik özelliklerini inceleyerek, bu maddelerin çift yönlü etkilerini anlamayı amaçlamaktadır. Özellikle vitaminlerin antioksidan ve antimutajenik özelliklerine ek olarak mutajenik özellikleri, ağır metallerin ise mutajenik özelliklerine ek olarak düşük dozlarda biyolojik sistemlerdeki olumlu etkilerine değinilmiştir.

2. AĞIR METALLER

Biyolojik açıdan “ağır”, düşük konsantrasyonlarda bile canlılar için toksik olabilen bir dizi metali, bazı durumlarda metalloidleri tanımlamaktadır [7]. Bu kategoriye yaklaşık 80 metal dahildir. Bilindiği üzere ağır metaller sadece su kaynakları, atmosfer ve gıda ürünleri kalitesini düşürmekle kalmaz, aynı zamanda besin zincirinde birikerek organizmaların ve insanların sağlığı üzerinde büyük bir tehdit oluştururlar [8]. Bu metallerin artan konsantrasyonları ve birikmesi canlı organizmalarda ciddi hasar verici etkilere ve farklı komplikasyonlara neden olabilir, hatta organizmanın ölümüne yol açabilmektedir [5]. Ayrıca hücre zarları, proteinler, mitokondriler ve DNA gibi hücre bileşenleriyle etkileşime girerek reaktif oksijen türü oluşturabilme potansiyeline sahiptir. Bu nedenle hücrede çeşitli hasarlara, transkripsiyonel değişikliklere ve DNA hasarına yol açarak birçok hastalığa, çoklu organ hasarına ve kansere neden olabilmektedir [9]. Yaygın maruz kalınan bazı ağır metaller arasında kurşun, civa, kadmiyum, nikel, krom ve arsenik bulunmaktadır. Bu metallerin bazıları insan vücudu için son derece zararlıdır ve düşük konsantrasyonlarda bile toksik olabilmektedir [10], [11]. Diğer taraftan hücrelerin metabolik aktiviteleri için bazı ağır metallere ihtiyaç duyulmaktadır. Örneğin demir, çinko, bakır ve manganez gibi metallerin çeşitli enzimlerin kofaktörleri olarak önemli rolleri bulunmaktadır. Bu metaller, vücutta kritik biyokimyasal süreçlerin düzenlenmesine yardımcı olmaktadır [10], [12]. Bu metallerin vücutta uygun seviyelerde bulunması önemlidir, hem eksikliği hem de fazlalığı sağlık sorunlarına yol açabilmektedir. Bu derleme kapsamında biyolojik öneme sahip bazı metallere değinilerek bu metallerin sağlığa yararlı etkileri ve toksik özelliklerine odaklanılmıştır.

2.1. Metallerin Biyolojik Önemi ve Toksik Etkileri

Organizmalar çeşitli metabolik aktivitelerin gerçekleşebilmesi için bazı ağır metallere eser miktarda ihtiyaç duymaktadır. Bu metaller organizmanın az miktarda ihtiyaç duyduğu vücut sıvı veya dokularında konsantrasyonları çok düşük düzeylerde olan mikro elementlerdir. Eser miktarda bulunan bu ağır metaller metabolizmanın sağlıklı yürüyebilmesi için özgül görev yapmaktadır ve bunların yerine başka kimyasallar geçemez. Bu metallere ilişkin bazı örnekler aşağıda verilmiştir.

Bakır (Cu), enerji metabolizması, antioksidan aktivite, nörotransmitterler ve kolajen sentezi dahil olmak üzere birçok hücresel süreçte rol oynamaktadır [13]. Bu metal iki değerlik durumundan ($Cu^{+} \Leftrightarrow Cu^{2+}$) geçiş yapmak için elektron alıp/vererek biyolojik oksidasyon–indirgeme (redoks) reaksiyonlarında önemli roller oynamaktadır [14]. Prokaryotlarda tanımlanan ve işlevi için bakıra ihtiyaç duyan sitokrom c oksidaz (COX), NADH dehidrojenaz-2 (ND2) ve Cu/Zn-süperoksit dismutaz (SOD1) enzimleri bulunmaktadır ve başka hiçbir metal bu enzimlerde işlevsel olarak bakırın yerini alamaz [15]. Bu elementin homeostazı insan vücudunda karmaşık mekanizmalarla düzenlenir ve eksikliği ya da fazla konsantrasyonlarda bulunması insan sağlığını çoklu mekanizmalar yoluyla etkileyebilir. İnsanlarda bakır eksikliğinin neden olduğu anemi, lökopeni, nötropeni ve pansitopeni gibi çok sayıda klinik semptom vardır [16], [17]. Ancak bakırın vücutta yüksek konsantrasyonlarda bulunması da toksik etkilere neden olabilmektedir ve bu elementin vücuda aşırı yüklenmesi kronik bakır toksisitesi ve akut bakır toksisitesi olarak iki yönlü olabilmektedir [18]. Kısa bir süre içinde çok sayıda bakır içeren maddeye maruz kalmanın neden olduğu akut toksik reaksiyonda bulantı, kusma, baş ağrısı, ishal, hemolitik anemi, gastrointestinal kanama ve karaciğer ve böbrek yetmezliği ve bazen de ölüm meydana gelebilmektedir [19], [20]. Kronik bakır toksisitesi ise düşük dozda bakır içeren maddelerin vücuda uzun süreli tekrarlanan girişinin neden olduğu kronik toksik reaksiyondur ve bu durum Wilson hastalığına neden olabilmektedir [21].

Kobalt (Co), B12 vitamininin (kobalamin) sentezinde kritik bir rol oynadığı için insan ve hayvanlarda metabolizma için gereklidir. Ayrıca bağışıklık tepkisini artırır ve antibakteriyel aktivite gösterir [22]. Kobalt et, süt ürünleri, deniz ürünleri ve bazı bitkiler gibi besinlerde doğal olarak bulunmaktadır. Bu elementin eksikliği anoreksi, kronik şişme ve anemiye yol açabilmektedir [23]. Ancak yüksek konsantrasyonları kusma, bulantı, ishal, kanama, düşük tansiyon, kalp hastalıkları, tiroit hasarı, saç dökülmesi, kemik kusurları ve bazı enzim aktivitelerinin inhibisyonu gibi sağlık sorunlarına neden olabilmektedir [24]. Bu element esas olarak sert metal endüstrisinde bağlayıcı olarak ve birçok alaşımın bileşeni olarak kullanılmaktadır. Uzun süreli yüksek düzeyde maruz kalma, kobaltın akciğerlerde birikmesine ve sert metal akciğer hastalığının ortaya çıkmasına neden olabilmektedir [25]. Günümüzde kobalt nanopartikülleri antioksidan, antimikrobiyal, antikanser ve antidiyabetik özellikleri sayesinde farklı ve çeşitli biyomedikal uygulamalarda kullanılmaktadır [26].

Mangan (Mn), vücutta çeşitli enzimlerin kofaktörü olarak gerekli olan hayati öneme sahip bir eser elementtir. Bu mineral, antioksidan savunma, enerji üretimi ve amino asit metabolizması gibi temel biyokimyasal süreçleri düzenleyen süperoksit dismutaz, glutatyon sentaz, piruvat karboksilaz ve arginaz gibi enzimlerin işlevlerinde kritik bir rol oynamaktadır [27]. Son çalışmalar manganın hem adjuvan olarak hem de tümör karşıtı bağışıklık tepkilerinde görev alan bir element olarak önemli roller oynadığını da ortaya koymuştur [28], [29]. Mangan genellikle kabuklu deniz ürünleri (özellikle midye ve istiridye), tam tahıllar, kuruyemişler, koyu yeşil yapraklı sebzeler, ananas ve çayda doğal olarak bulunmaktadır [30]. Bu elementin eksikliği, kemik gelişiminde bozulmalar, zayıf büyüme ve üreme sorunları gibi belirtilerle kendini gösterebilmektedir. Ayrıca daha önce gerçekleştirilen bir çalışmada mangan yetersizliği olan farelerde tümör büyümesi ve metastazın önemli ölçüde arttığı bildirilmiştir [28]. Mangan eksikliği genellikle nadirdir ve çoğunlukla beslenme yetersizliklerinden kaynaklanır.Ancak diğer ağır metallerde de olduğu gibi fazlası ise toksik olabilmektedir. Özellikle endüstriyel maruziyet durumlarında, uzun süreli yüksek mangan alımı sinir sistemi üzerinde olumsuz etkiler yaratabilir ve Manganizim/Parkinsonizm olarak adlandırılan Parkinson hastalığı benzeri semptomlara yol açabilmektedir [31]. Bu toksisite, genellikle işçilerde veya kontamine gıda ve su tüketiminde görülür ve kardiyovasküler fonksiyonların da etkilenmesine neden olabilmektedir [27], [32].

Demir (Fe), oksijenin taşınmasında ve depolanmasında hayati bir görev üstlenen hemoglobin ve miyoglobinin yapısal bileşenidir. Ayrıca, DNA sentezi, hücre bölünmesi ve çeşitli enzimlerin aktivitesinde de yer almaktadır [33], [34]. Besinsel kaynaklarında hem ve non-hem formda bulunur. Hem demir, hayvansal gıdalarda, özellikle kırmızı et, karaciğer ve deniz ürünlerinde yüksek oranda bulunur ve vücut tarafından daha kolay emilir. Non-hem demir ise bitkisel kaynaklarda, özellikle baklagiller, kuruyemişler, yeşil yapraklı sebzeler ve demirle zenginleştirilmiş tahıllarda bulunur. Örneğin, ıspanak, mercimek ve beyaz fasulye gibi gıdalar önemli non-hem demir kaynaklarıdır [34]. Demir eksikliği dünya genelinde yaygın bir beslenme sorunudur ve anemiye neden olmaktadır. Demir eksikliği anemisi, yorgunluk, halsizlik, solgunluk, baş dönmesi ve nefes darlığı gibi belirtilerle kendini gösterir. Ayrıca, bilişsel işlev bozukluklarına, bağışıklık sistemi zayıflamasına ve fiziksel performans düşüklüğüne yol açabilmektedir [35]. Ancak bu elementin de yüksek konsantrasyonları sağlık açısından riskler taşımaktadır. Vücutta aşırı demir birikmesi, oksidatif stres ve hücresel hasara yol açabilmektedir. Bu durum genellikle genetik hastalıklar (örneğin, herediter hemokromatoz) veya demir takviyelerinin aşırı kullanımı nedeniyle ortaya çıkmaktadır. Yüksek dozlarda demir alımı, özellikle çocuklarda ciddi zehirlenmelere yol açabilmektedir. Aşırı demir karaciğer, kalp ve pankreas gibi organlarda hasara neden olabilmekte ve kronik hastalık riskini artırabilmektedir [36].

Magnezyum (Mg), 300'den fazla enzimatik reaksiyon (enerji üretimi, nükleik asit sentezi, kas ve sinir fonksiyonları gibi) için kofaktör olarak gerekli olan temel bir elementtir ve bu nedenle çok sayıda metabolik yolun biyokimyasal işleyişi için hayati önem taşımaktadır [37]. Ayrıca migren tedavisinde etkili olup, intravenöz ve oral formlarıyla atakların şiddetini ve sıklığını azaltmaktadır [38]. Magnezyumun önemli kaynakları arasında yeşil yapraklı sebzeler, kuruyemişler, tohumlar, tam tahıllar ve bazı balık türleri yer almaktadır. Bu elementin eksikliği, kas krampları, yorgunluk, iştahsızlık, mide bulantısı ve anormal kalp ritmi gibi belirtilere yol açmaktadır [39]. Eksiklik, özellikle alkol bağımlılığı, yaşlılık, malabsorpsiyon sorunları ve Tip 2 diyabet gibi risk faktörlerine sahip kişilerde daha yaygındır [40], [41]. Öte yandan, aşırı magnezyum alımı, genellikle gıdalardan kaynaklanmaz, uzun süreli yüksek dozda magnezyum takviyesi ile gerçekleşir ve böylelikle toksik seviyelere ulaşabilmektedir. Bu durumda mide bulantısı, ishal, kas zayıflığı ve düşük kan basıncı gibi belirtiler ortaya çıkabilmektedir. Böbrek hastalığı olan bireylerde magnezyum toksisitesi riski daha yüksektir, çünkü vücut magnezyumu normalden daha yavaş bir şekilde atabilir. Bu durum, magnezyumun birikmesine ve toksik düzeylere ulaşmasına neden olabilir. Bu nedenle böbrek hastalığı olan kişilerin magnezyum takviyelerini veya magnezyum içeren ilaçları kullanırken dikkatli olmaları önemlidir [42].

Çinko (Zn), katalizör, yapısal ve düzenleyici iyon olmak üzere üç ana biyolojik rolü olan organizmadaki en önemli eser elementlerden biridir. DNA sentezi, protein üretimi, hücre bölünmesi, bağışıklık sistemi fonksiyonu ve yara iyileşmesi gibi birçok biyokimyasal süreçte merkezi rol oynamaktadır [43]. İstiridye, kırmızı et, kümes hayvanları, baklagiller, fındık, tohumlar, tam tahıllar ve süt ürünlerine ek olarak güçlendirilmiş kahvaltı gevrekleri, kabak çekirdeği, mercimek ve bazı süt ürünleri de çinko açısından zengindir. Önemli yapısal fonksiyonu olan bu elementin eksikliğinde büyüme geriliği, iştahsızlık, bağışıklık fonksiyonlarının bozulması, saç dökülmesi, ishal, cilt lezyonları ve yara iyileşmesinde gecikme gibi sorunlar görülebilmektedir [44]. Vücuttaki düşük çinko seviyeleri aynı zamanda apoptoz, organ tahribatı, DNA yaralanmaları ve reaktif oksijen türleri yoluyla hücresel bileşenlerde oksidatif hasar gibi birçok fizyolojik bozukluktan da sorumludur. Oksidatif hasar, kronik inflamasyona yol açarak kalp hastalıkları, kanser, alkole bağlı hastalıklar, kas kasılması ve nöro-patogenez gibi çeşitli kronik hastalıklara yol açmaktadır [45]. Ayrıca gelişmekte olan ülkelerde bebeklerde ve çocuklarda akut ishalin tedavisinde kullanılmaktadır ve bu sayede milyonlarca yaşamın kurtarılması sağlanmıştır. Ek olarak Wilson hastalığının tedavisi ve bakım terapisi için onaylanmış bir ilaç olarak da kullanılmaktadır [46]. Ancak çinkonun fazlası da vücut için zararlıdır. Aşırı çinko alımı mide bulantısı, kusma, iştahsızlık, karın krampları, ishal ve baş ağrısı gibi semptomlara neden olabilmektedir [47]. Kronik yüksek dozda çinko alımı bakır emilimini engelleyerek bakır eksikliğine ve nörolojik bozukluklara yol açabilmektedir. Ayrıca bağışıklık sistemi fonksiyonlarını bozabilir ve lipoprotein seviyelerinde değişikliklere neden olabilir [48], [49]. Çinko, sağlıklı bir yaşam sürdürmek için belli miktarda alınımı hayati öneme sahip bir metaldir. Bu metalin hem eksikliği hem de fazlalığı ciddi sağlık sorunlarına yol açabilir. Bu nedenle, dengeli bir diyetle yeterli miktarda çinko alımına özen gösterilmelidir.

Krom (Cr), özellikle insülinin etkisini artırarak karbonhidrat (şeker), yağ ve protein metabolizmasında kritik bir rol oynamaktadır [50]. Bu element kas kütlesinin artmasına, kan şekeri seviyesinin düzenlenmesine ve sağlıklı kan basıncı seviyesinin korunmasına yardımcı olur [51]. Brokoli, karaciğer, tam tahıllar, patates, sarımsak, yeşil fasulye, bira mayası ve bazı deniz ürünleri gibi besinler iyi krom kaynaklarıdır. Bu elementin eksikliği nadir olmakla birlikte, insülin direnci, kan şekeri dengesizlikleri, artan diyabet riski ve kilo alımı gibi sağlık sorunlarına yol açabilmektedir [52]. Ancak fazla konsantrasyonlarda bulunması toksik etkilere neden olmaktadır [6], [53], [54]. Ayrıca bu elementin Cr (VI) ve Cr (III) formları sağlık açısından büyük önem taşımaktadır. Cr (VI) doğada daha yaygın olan formdur ve hücreye alındığında, glutatyon ve askorbik asit gibi hücresel redoks ajanları tarafından sırasıyla Cr (V) ve Cr (III) formlarına indirgenir [55], [56]. Literatürdeki çalışmalara göre, Cr (III) biyolojik olarak daha az toksik olmasına rağmen, yüksek dozda Cr (VI) maruziyeti sonucunda hücre içinde birikerek DNA ve proteinlere bağlanıp genotoksik etkilere neden olabilmektedir [57]. Cr (VI)'nın neden olduğu bu redüksiyon süreci sırasında oluşan serbest radikaller, hücresel bileşenlere zarar vererek oksidatif stres, DNA hasarı ve apoptozis gibi süreçleri tetikleyebilmektedir [58], [59]. Bu nedenle Cr (VI)'nın yüksek dozlarda maruziyeti, hücre içi Cr (III) konsantrasyonunu artırarak zararlı etki göstermektedir [60]. Kromun uzun süreli maruziyeti ve biyobirikimi, alerjik reaksiyonlar, anemi, mide ve ince bağırsakta yaralar, sperm ve erkek üreme sisteminde toksik etkiler yaratabilmektedir [61]. Kısacası krom, vücut fonksiyonları için gereklidir, ancak dengeli bir diyetle uygun miktarda alınması önemlidir. Fazla krom alımının olumsuz etkilerinden kaçınmak için dikkatli olunmalıdır.

Biyolojik süreçlerin gerçekleşebilmesi için gerekli olan metaller insan vücudunda hayati biyokimyasal süreçlerin düzgün işleyişi için önemlidir. Bu elementler enzimlerin aktivasyonundan DNA sentezine kadar birçok kritik rol oynar ve sağlığımızın korunmasında vazgeçilmezdir. Ancak bu elementlerin fazlası toksik etkiler göstererek cilt rahatsızlıkları, astım ve kanser gibi ciddi sağlık problemlerine neden olabilir. Bu nedenle eser elementlerin dengeli bir şekilde alınması büyük önem taşır. Vücudun ihtiyaç duyduğu miktarda alınan elementler sağlıklı bir yaşamın sürdürülebilmesi için kritik öneme sahiptir. Dolayısıyla, beslenme alışkanlıkları bu elementlerin dengeli bir şekilde karşılanmasına yönelik düzenlenmelidir.

3. VİTAMİNLER

Canlıların yaşamları boyunca çeşitli fizyolojik fonksiyonları koordine etmek için değişen miktarlarda gereken temel besinler vardır. Temel besin maddeleri insanlarda ya hiç sentezlenemez ya da yetersiz miktarda sentezlenebilir ve bu nedenle diyet yoluyla elde edilmelidir. Vitaminler vücudun normal işleyişi için gerekli olan temel mikrobesinlerdir. Temel hücresel fonksiyonları destekleyen çeşitli temel metabolik yollarda önemli rol oynarlar. Vücutta eksiklikleri veya yetersizlikleri durumunda çeşitli sağlık sorunları oluşabilmektedir. Şu anda bilinen ve insanlar için gerekli olan 13 farklı vitamin vardır. Bu vitaminler genellikle yağda çözünen vitaminler ve suda çözünen vitaminler olmak üzere iki ana grupta sınıflandırılmaktadır.

3.1. Yağda Çözünen Vitaminlerin Toksik ve Koruyucu Etkileri

Organizmalar çeşitli metabolik aktivitelerin gerçekleşebilmesi için bazı ağır metallere eser miktarda ihtiyaç duymaktadır. Bu metaller organizmanın az miktarda ihtiyaç duyduğu vücut sıvı veya dokularında konsantrasyonları çok düşük düzeylerde olan mikro elementlerdir. Eser miktarda bulunan bu ağır metaller metabolizmanın sağlıklı yürüyebilmesi için özgül görev yapmaktadır ve bunların yerine başka kimyasallar geçemez. Bu metallere ilişkin bazı örnekler aşağıda verilmiştir.

A vitamini (retinol), hem hayvansal hem de bitkisel kökenli, yağda çözünen, yaşam için gerekli bir vitamin grubudur. Hayvansal ürünlerden (karaciğer, balık yağı, süt ve süt ürünleri vs.) A vitamini (retinol ve yakın türevleri olarak) ve sebzelerden (kırmızı biber, koyu yeşil yapraklı ve turuncu-sarı renkli sebzeler) provitamin A (karotenoidler) şeklinde diyetle sağlanabilmektedir [62]. Retinol, vücutta en bol bulunan form olmasına rağmen, ATRA (all-trans retinoik asit) A vitaminin başlıca etkin formudur. Bu vitamin görme, bağışıklık sistemi, hücresel büyüme ve farklılaşma dahil olmak üzere çok sayıda vücut fonksiyonu için gereklidir [63]. Ayrıca bazı araştırmalar A vitamininin ve özellikle aktif formu olan retinoik asidin antikanser etkilerini bildirmiştir. Retinoik asit hücre farklılaşması, büyümesi ve apoptozisinde önemli rol oynayan bir retinoid olup kanser hücrelerinin çoğalmasını engelleyebilmektedir [64], [65]. A vitamini eksikliği, gece körlüğü, enfeksiyon riskinin artması ve çocuklarda büyüme ve gelişmenin bozulması gibi ciddi sağlık sorunlarına yol açabilmektedir [66]. Bununla birlikte, aşırı A vitamini alımı toksik olabilir ve A hipervitaminozu olarak bilinen bir duruma yol açabilir. Bu toksisitenin belirtileri arasında karaciğer hasarı, baş ağrıları, bulantı, cilt kuruluğu ve ciddi vakalarda kemik ağrısı ve nörolojik bozukluklar yer almaktadır [67], [68]. A vitaminin aniden aşırı tüketilmesi akut zehirlenmeye yol açar. Akut toksisitede gözlenen başlıca semptomlar arasında bulantı, sinirlilik, iştahsızlık, kusma, bulanık görme, baş ağrısı, saç kaybı, kas ağrısı, kanama, zayıflık, uyuşukluk ve değişmiş mental durum bulunmaktadır [68], [69]. Retinoid uygulaması sonrası en sık görülen biyokimyasal yan etki hipertrigliseridemidir. Tedavinin başlamasından birkaç hafta sonra ortaya çıkar. Sonunda bu yüksek trigliserid seviyeleri karaciğer hasarına yol açar, bu da fibröz ve hepatik stellat hücre aktivasyonuna neden olarak potansiyel olarak geri dönüşümsüz karaciğer hasarına neden olur. Öte yandan, oral retinoidler çatlamış dudaklar, baş ağrısı, yüz kızarması, karın ağrısı, baş dönmesi ve koordinasyon kaybına neden olabilmektedir [69]. Ayrıca daha önce fare modelleri üzerinde gerçekleştirilen bir çalışmada uzun süreli A vitamini diyet alımının spermatogenezi bozduğu bildirilmiştir [3]. Bu nedenle, optimal sağlığı sağlamak için dengeli bir A vitamini alımını sürdürmek çok önemlidir. Literatür, A vitamininin hem kritik rollerini hem de potansiyel tehlikelerini kapsamlı bir şekilde belgeleyerek, tüketiminin dikkatli bir şekilde yönetilmesi gerektiğinin altını çizmektedir [63], [66], [67], [68], [69], [70].

D vitamini (kalsiferol), vücut için birçok önemli fonksiyona sahip olan yağda çözünen bir vitamindir. Kalsiyum ve fosfor gibi minerallerin vücutta emilimini düzenleyerek kemik ve diş mineralizasyonunu etkilemektedir [71]. İskelet kasları, bağışıklık düzenlemesi, kardiyovasküler sağlık ve metabolik aktiviteler üzerinde de işlevleri olduğu bilinmektedir. Bu vitamin doğal olarak somon, uskumru gibi yağlı balıklarda, morina karaciğeri yağında ve yumurta sarısında bulunur. Ayrıca, zenginleştirilmiş süt ve süt ürünleri, bitkisel sütler ve bazı mantar türleri de önemli D vitamini kaynaklarıdır. D vitamini, doğal olarak sınırlı sayıda besinde bulunur, bu nedenle zenginleştirilmiş gıdalar ve güneş ışığına maruz kalma, bu önemli vitaminin yeterli seviyelerde alınmasını sağlamada kritik rol oynar. D vitamini, vücutta aktif hale gelmeden önce birkaç öncü formdan geçer ve güneş ışığı bu süreçte kritik bir rol oynar. Ciltte bulunan 7-dehidrokolesterol, güneşten gelen ultraviyole B ışınları ile etkileşime girerek D3 vitamini (kolekalsiferol) formuna dönüşür. Güneş ışığına yeterli düzeyde maruz kalmak, bu nedenle D vitamini üretimi için hayati önem taşır [72]. Bitkisel kaynaklarda bulunan D2 vitamini (ergokalsiferol) ve D3 vitamini, karaciğer ve böbreklerde aktif forma dönüştürülerek vücutta kullanılabilir hale gelir [73]. Bu süreçler, D vitamininin kemik sağlığı ve bağışıklık sistemi üzerindeki etkilerini optimize etmek için gereklidir. Genellikle D vitamininin eksikliği veya yetersiz emilimi sonucunda raşitizm/osteomalazi ortaya çıkar. Raşitizm, çocukluk döneminde kemiklerin gelişme döneminde görülen bir hastalıktır. Bu hastalıkta, kemikler yeterince mineralize olmaz ve bu da kemiklerin zayıflamasına, eğrilmesine ve kafa şeklinin anormal bir şekilde büyümesine yol açmaktadır. Osteomalazi, genellikle yetişkinlik döneminde görülen bir hastalıktır ve raşitizme benzer semptomlara sahiptir. Kemik zayıflığı daha belirgindir ve ağrılı kemikler, kas zayıflığı, yorgunluk hissi ve kırılgan kemikler gibi semptomlar daha yaygındır. Ancak D vitamini takviyesinin uzun süreli ve aşırı tüketimi, hiperkalsemi veya hiperfosfatemiye neden olarak ektopik yumuşak doku mineralizasyonuna yol açabilmektedir. Örneğin takviye aracılığıyla serum kalsiyum ve fosfat seviyelerindeki artış ve sonraki aşırı dozda kalsiyum-fosfat ürününün oluşumu, böbrekler (nefrokalsinoz) ve kan damarları (vasküler kalsifikasyon) dahil olmak üzere çeşitli organlarda birikime neden olabilmektedir. Bu tür vasküler kalsifikasyon, aterosklerotik plaklarla birleştiğinde koroner arterleri de içerirse, sonuçlar ölümcül olabilmektedir. 2011 yılında Hindistan'da gerçekleştirilen bir çalışmada D vitamini eksikliği açısından endemik bir bölgede yüksek dozda D vitamini ile tedavi edilen hastalarda kusma, poliüri, polidipsi, ensefalopati ve böbrek fonksiyon bozukluğu saptandığı, ayrıca hastaneye başvuran hastalardan birinin eşzamanlı sepsis sonucu çoklu organ yetmezliğinden dolayı hayatını kaybettiği bildirilmiştir [74]. D vitamini toksisitesi nadirdir ve bu vitaminin toksik etkisi genellikle D vitamini eksikliğinin aşırı vitamin takviyesinden kaynaklı olarak gerçekleştirilmeye çalışılan tedavilerde ortaya çıkmaktadır [75], [76], [77], [78]. Bu nedenle hastaların ve reçete edenlerin D vitamini aşırı dozunun potansiyel tehlikeleri konusunda daha bilinçli olmaları gerektiğini vurgulamakta fayda vardır.

E vitamini (tokoferol) yalnızca diyetle elde edilen ve yağda çözünen önemli bir antioksidandır. 1920'lerde farelerin üreme için ihtiyaç duyduğu temel bir besin öğesi olarak keşfedilmiştir [79]. Bu vitamin özellikle bitkisel yağlarda, tohumlarda, fındıkta ve yeşil yapraklı sebzelerde bol miktarda bulunur. E vitamini ile ilgili yaklaşık 8 farklı molekül vardır (alfa-tokoferol, beta-tokoferol, gama-tokoferol, delta-tokoferol, alfa-tokotrienol, beta-tokotrienol, gama-tokotrienol ve delta-tokotrienol), ancak insanlarda baskın molekül alfa-tokoferoldür [80]. Yapılan çalışmalarda E vitamininin meme, prostat, kolon ve akciğer kanseri gibi çeşitli kanser türlerinde hücre proliferasyonunu inhibe ettiği ve apoptozu indüklediği bildirilmiştir [81]. Örneğin alfa-tokoferolün prostat kanseri riskini azalttığı ve tokotrienollerin ise meme kanseri hücrelerinde tümör büyümesini baskıladığı belirlenmiştir [82]. E vitamini peroksil radikal temizleyici özelliklere sahiptir ve toksisitesi kanama riskinin artmasıyla ilişkilendirilirken, eksikliği nörolojik hastalıklar ve anemi ile ilişkilendirilmiştir [83]. E vitamini toksisitesi nadir görülmesine rağmen, yüksek dozlarda uzun süreli alımının ciddi sağlık sorunlarına yol açabileceği bilinmektedir. Literatürdeki çalışmalar, özellikle 400 IU/gün üzerinde E vitamini takviyesi alımının kanama riskini artırabileceğini ve bazı bireylerde gastrointestinal sorunlara neden olabileceğini göstermektedir [84]. Bu vitamininin yüksek dozları, K vitamini bağımlı pıhtılaşma faktörlerinin antagonizmasına yol açarak kanama eğilimini artırabilmektedir. Örneğin, Schürks vd. [85] yaptığı bir meta-analiz, yüksek doz E vitamini takviyesinin hemorajik (kanamayla ilgili) inme riskini artırabileceğini ortaya koymuştur. Bunun yanı sıra, bazı çalışmalar yüksek doz E vitamini alımının kardiyovasküler hastalık riski taşıyan bireylerde mortaliteyi artırabileceğini bildirmiştir [86]. Bu durum, E vitamini takviyelerinin potansiyel yararları ile risklerinin dikkatlice değerlendirilmesi gerektiğini göstermektedir. Ayrıca Sesso vd. [87] yüksek doz E vitamini takviyesinin prostat kanseri insidansını artırabileceğini bildirmiştir. Bu bulgular, E vitamini takviyelerinin dozunun dikkatli bir şekilde ayarlanması ve aşırı dozlardan kaçınılması gerektiğini vurgulamaktadır.

K vitamini (filoquinon, menakinon) karaciğerde pıhtılaşma faktörleri II (protrombin), VII, IX ve X ile çeşitli proteinlerin sentezi ve aktivasyonu için gerekli bir kofaktördür ve üç formu bilinmektedir: vitamin K1 (filokinon), vitamin K2 (menakinonlar) ve vitamin K3 (menadion) [88]. Vitamin K1, kan dolaşımındaki ana formdur ve özellikle yeşil yapraklı sebzeler gibi besin kaynaklarıyla sağlanır. Vitamin K2, özellikle yumurta sarısı, tavuk, dana eti, sebzeler gibi ürünlerde bulunur. Ayrıca, bağırsak florasından da (intestinal bakteriler tarafından) sentezlenir. Vitamin K3 ise sentetik bir formdur. K vitamininin kemik sağlığı üzerindeki olumlu etkileri ve antioksidan özellikleri nedeniyle kardiyovasküler hastalıklar ve osteoporoz gibi durumlarda potansiyel koruyucu etkileri bildirilmiştir [89]. Ayrıca antitoksik özellikleri de dikkate değerdir; bazı çalışmalar, K vitamininin oksidatif stresi azaltarak ve inflamasyonu baskılayarak hücre koruyucu etkiler gösterebileceğini öne sürmüştür [90], [91], [92]. K vitamini toksisitesi nadirdir ancak bu vitaminin de özellikle yüksek dozlarda uzun süreli alımı bazı sağlık sorunlarına yol açabilmektedir. İnsanlarda K vitamini toksisitesi ile ilgili veriler sınırlı olmakla birlikte, özellikle yeni doğanlarda yüksek doz K3 vitamini enjeksiyonlarının toksik etkileri bildirilmiştir [93]. K2 vitamini ile ilgili yapılan bir çalışma ise fareler ve sıçanlar üzerindeki etkilerinin önemli bir toksisite göstermediği, akut toksisite testinde farelerde 2000 mg/kg dozda herhangi bir toksisite gözlemlenmezken, sıçanlarda 90 gün boyunca uygulanan 10 mg/kg/gün dozu ile ilgili de olumsuz etki bulunmamıştır [94]. Ancak Ansell vd. [95] oral antikoagülan kullanan hastalarda yüksek doz K vitamini alımının bu ilaçların etkinliğini azaltarak tromboz riskini artırabileceğini bildirilmiştir. Bu bulgular, K vitamini takviyelerinin dikkatli bir şekilde uygulanması ve gereksiz yüksek dozlardan kaçınılması gerektiğinin önemini vurgulamaktadır.

3.2. Suda Çözünen Vitaminlerin Toksik ve Koruyucu Etkileri

C Vitamini (askorbik asit) genel olarak bir antioksidan olarak bilinmektedir ve mutajenik etkilere sahip birçok ajana karşı antimutajenik etki gösterdiği ile ilgili çalışmalar mevcuttur [96], [97]. Ancak, fizyolojik rolü çok daha geniştir ve demir emilimini kolaylaştırmadan hormon regülasyonuna kadar farklı süreçleri içermektedir [98]. Çoğu omurgalıya kıyasla, kobaylar, yarasalar, ötücü kuşlar ve insanlar da dahil olmak üzere primatlar, L-gulono-1,4-lakton oksidazı eksik oldukları için C vitamini sentezleyemezler ve bu nedenle diyetten C vitamini alımına tamamen bağımlıdırlar. Algler ve fotosentetik protistler de dahil olmak üzere tüm bitki türlerinde C vitamini sentezlenmektedir [99]. Bu vitaminin eksikliğinde insanlarda iskorbüt olarak bilinen bir hastalık ortaya çıkar. Bu hastalığın tipik belirtileri kas zayıflığı, şişmiş ve kanayan diş etleri, diş kaybı, anemi, yara iyileşmesinde bozulma ve kilo kaybıdır. İskorbüt potansiyel olarak ölümcüldür ve ani ölüm, serebral/kardiyak kanama veya pnömoni sonucu meydana gelebilmektedir [98]. İlk belirtilerden bazıları olan bitkinlik ve yorgunluk, plazma seviyelerinin yaklaşık 20 µM'nin altında olması durumunda görülür ve bu durum, karnitin sentezindeki azalmaya bağlı olabilmektedir. Çünkü karnitin eksikliği kaslarda ve diğer dokularda yağ asitlerinin oksidasyonunun azalmasına neden olmaktadır. Askorbik asidin eksikliği her ne kadar vücut için ölümcül sonuçlar doğurabiliyor olsa da bazen prooksidant etki gösterebilmektedir. Örneğin daha önceki çalışmalarda $CoCl_2$ ile birlikte C vitaminine maruziyetin $CoCl_2$ toksisitesini artırdığı bildirilmiştir [6]. Ayrıca C vitamini insanda kısmen oksalata metabolize olur ve doza bağımlı olarak idrarda oksalat seviyelerini artırarak idrar taşı oluşumuna neden olabilir. Günde 1 g'dan yüksek dozlarda vitamin C alımı taş oluşumu riskini %41 oranında artırdığı bildirilmiştir [100]. Tek dozda alınması (özellikle 5-10 g'lık yüksek bir doz) geçici osmotik ishale, karın şişkinliğine ve ağrıya neden olabilmektedir. İntravenöz vitamin C veya çok yüksek oral vitamin C dozları glukoz-6-fosfat eksikliği olan hastalarda hemolizi tetikleyebilmektedir [101]. Yüksek doz C vitamini alımının bazı sağlık riskleri taşıdığı açıktır. Gastrointestinal rahatsızlıklar, böbrek taşı oluşumu, hemolitik anemi ve potansiyel diğer yan etkiler göz önüne alındığında, C vitamini takviyesi alırken önerilen günlük alım miktarlarına dikkat edilmesi önemlidir.

B vitaminleri suda çözünen ve vücutta enerji üretimi, hücre metabolizması ve sinir sistemi fonksiyonları gibi birçok hayati süreçte rol oynayan sekiz farklı (B1 (tiyamin), B2 (riboflavin), B3 (niasin), B5 (pantotenik asit), B6 (piridoksin), B7 (biyotin), B9 (folat), B12 (kobalamin)) vitaminden oluşan bir gruptur. Bu vitaminler genellikle "B kompleks vitaminleri" olarak adlandırılır ve her biri belirli biyolojik işlevlere sahiptir [102]. Tiyamin, hücrelerdeki karbonhidratlardan enerji üretimine yardımcı olur ve sinir sisteminin düzgün işleyişi için gereklidir. Tam tahıllar, et, balık, baklagiller, fındık ve yumurta gibi gıdalarda bol miktarda bulunur. Riboflavin, flavin adenin dinükleotidinin (FAD) öncüsüdür ve karbonhidratların, amino asitlerin ve lipitlerin aracı metabolizmasında hayati bir rol oynamaktadır. Süt ve süt ürünlerinde, yumurtada, yeşil yapraklı sebzelerde ve karaciğer gibi organ etlerinde yer alır. Et, balık, tavuk, yer fıstığı ve tam tahıllarda bulunan niasin, hücresel metabolizma için gereklidir ve Krebs döngüsünde ve vücutta birçok molekülün sentezinde önemli bir rol oynayan koenzim öncüsüdür. Bu vitamin kimyasal olarak nikotinik asit olarak bilinir ve amidi nikotinamid olarak adlandırılır. Pantotenik asit, anti-stres vitamini olarak bilinir ve hemen hemen her türlü gıdada, özellikle et, avokado, yoğurt ve tam tahıllarda mevcuttur. Hücresel metabolizmada rol oynayan koenzim A ile açil taşıyıcı protein biyosentezinin öncüsü olarak işlev görmektedir. Piridoksin zihinsel fonksiyonun düzenlenmesinde önemlidir ve homosisteinin yeniden metilasyonunda rol oynamaktadır. Bu vitamin özellikle tavuk, balık, patates, muz ve nohut gibi besinlerde bulunur. H vitamini olarak da bilinen biyotin, yumurta sarısı, badem, fındık, soya fasulyesi ve tam tahıllarda bulunur. Karbonhidrat, yağ ve protein metabolizması da dahil olmak üzere çeşitli metabolik süreçlerde önemli bir rol oynar ve sağlıklı bir cilt ile sinir sisteminin korunması için gereklidir. Folat özellikle DNA sentezi, onarımı ve metilasyonu için gereklidir ve doğal olarak yeşil yapraklı sebzeler, baklagiller, meyveler ve zenginleştirilmiş tahıllarda yer alır. 1943 yılında folatın oksitlenmiş sentetik bir formu olan folik asit sentezi yapılmıştır ve şu an da özellikle gıdaların zenginleştirilmesi için kullanılmaktadır. Kobalamin özellikle et, balık, yumurta, süt ürünleri ve bazı zenginleştirilmiş gıdalarda bolca bulunur. Bu vitamin beynin ve sinir sisteminin normal işleyişinde önemli bir rol oynamaktadır. Karbonhidratların, proteinlerin ve lipitlerin hücresel metabolizmasında yer alır ve miyelin oluşumunda ve sinir sisteminin normal fizyolojisinde kofaktör olarak görev yapar [103], [104], [105], [106], [107]. Her ne kadar bu vitaminler vücut için gerekli ve birçok önemli fonksiyonun öncüsü olsalar da yüksek dozlarda toksik özellikler gösterebilmektedir. Örneğin yüksek dozlarda niasinin ciltte kızarıklık, kaşıntı, mide rahatsızlıkları ve karaciğer toksisitesi gibi yan etkilere yol açabildiği bildirilmiştir [108]. Yüksek doz folik asit alımı, nöbetlere eğilimli bireylerde nöbet sıklığını artırabilir ve B12 vitamini eksikliğinin belirtilerini engelleyebilir. Bu durum nörolojik hasarın ilerlemesine neden olabilmektedir [109], [110]. Yüksek dozda piridoksin özellikle uzun süreli kullanımda, nöropatiye yol açarak sinir hasarı ve duyu bozukluklarına neden olabildiği bildirilmiştir [111]. Morales-Gutierrez vd. [3] şiddetli pernisiyöz anemi nedeniyle siyanokobalamin dozu ile tedavi edilen bir hastada 12 mg dozdan sonra akne, çarpıntı, anksiyete, yüz kızarıklığı, baş ağrısı ve uykusuzluk olduğunu bildirmiştir. Araştırmacılar bu beklenmedik kobalamin toksisitesi sonucunda herhangi bir ilacın uygulanmasının tamamen güvenli olmadığını vurgulamıştır. B vitaminleri enerji üretimi, hücre metabolizması ve sinir sistemi fonksiyonları gibi temel biyolojik süreçlerde kritik rol oynayan, vücudun sağlığı için vazgeçilmez maddelerdir. Ancak, literatür çalışmaları da göstermektedir ki bu vitaminlerin aşırı alımı, beklenmedik toksik etkiler ortaya çıkarabilmektedir. Bu durum B vitaminlerinin doğru dozda kullanılmasının önemini bir kez daha vurgulamaktadır. Dolayısıyla, bireylerin vitamin alımlarını dikkatlice yönetmeleri ve sağlık profesyonellerinin bu süreçte doğru rehberlik sağlaması gerekmektedir. Böylece, bu hayati maddelerin yararlarından en iyi şekilde faydalanmak mümkün olurken, olumsuz etkileri de minimize edilebilir.

Suda çözünen vitaminler genellikle vücutta birikmezler çünkü fazla alındıklarında idrar yoluyla hızla atılırlar. Ancak, aşırı tüketim veya takviye durumlarında kısa süreli veya kısmen birikim oluşabilir. Bu vitaminlerin normal şartlarda vücutta birikmemesi avantajlı bir durum olmasına karşın, yukarıda da bahsedildiği gibi aşırı tüketim ve özellikle yüksek dozda takviyeler kısa süreli birikime ve dolayısıyla potansiyel toksisiteye neden olabilir. Bu durum suda çözünen vitaminlerin güvenli kullanımı konusunda dikkatli olunması gerektiğini göstermektedir.

4. SONUÇ

Metaller ve vitaminler, insan sağlığı üzerinde karmaşık etkiler yaratabilmektedir. Doza bağlı olarak bu maddelerin yararlı veya zararlı olabileceği açıkça görülmektedir. Vitamin toksisitesinin yüksek doz tedavilerde ortaya çıkabileceği ve bu konuda dikkatli olunması gerektiği, özellikle önemli bir bulgu olarak öne çıkmaktadır. Sağlık profesyonellerinin, bireylerin maruziyetlerini doğru bir şekilde yönetmesi ve optimal konsantrasyonları belirlemesi, sağlık risklerinin minimize edilmesi açısından kritik öneme sahiptir. Bu nedenle, bu derlemenin sonuçları hem bireyler hem de sağlık alanında çalışan profesyoneller için dikkate değer bir kaynak niteliği taşımaktadır.

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Çıkar Çatışması/Ortak Çıkar Beyanı

Yazarlar tarafından herhangi bir çıkar çatışması veya ortak çıkar beyan edilmemiştir.

Yazarların Katkısı

İlk yazar %40, ikinci yazar %20 ve üçüncü yazar %40 katkıda bulunmuştur.

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Research Article

Effect of Wildfires on Mobility of Metribuzine Herbicide in Agricultural Soil

Gökçe AKYOL

Article Info

Author e-mail: gakyol@ua.edu

Institution: Alabama Unıversity

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ABSTRACT

Metribuzine has been used extensively to control weeds and grasses, which could cause severe groundwater and soil contamination. Wildfires are an important process in environment, which can be severe for many areas and could have an effect on soil properties. The purpose of this research was to evaluate the effect of wildfires for the fate and transport of atrazine for agricultural soil. Miscible-displacement experiments were used for the objectives. Results showed that the soil-water distribution coefficient (Kd) from metribuzine was 0.28 and 0.13 L/Kg for soils prior to and after wildfire, respectively. Results showed that organic matter fraction of soil has predominantly played role on sorption of metribuzine and exhibited rate-limited sorption-desorption. In addition, sorption of metribuzine onto soil after wildfire was significantly lower which likely causes more risk of contamination for groundwater resources.

1. INTRODUCTION

Wildfires are very important natural process for the environment and their increasing frequency and severity in effected areas could lead to change in ecosystems. After wildfire, loss of vegetation and changes to soil properties could cause flowing of water over the land surface during storms and delivery of debris and sediments to surface water. Wildfires could also cause predominant impact on the physical and chemical properties of the soil. Wildfire burns the vegetation and organic matter components in soil and that could increase soil density and reduce permeability and porosity.

Soil and groundwater contamination by pesticides tends to pose a risk to environment and human health. The negative effect of herbicide loading on environment and human health and their mobility in various soils has been under attention las few decades. Metribuzine is one of the most used herbicide to control weeds and grasses around agricultural part of countries. Sorption and desorption phenomenon plays an important role for mobilities of herbicides in soils that has predominant effect on groundwater and soil remediation efficacy [1]. Soil paramaters such as pH, clay content, organic carbon content and Cationic Exchange Capacity (CEC) have been studied to have impact on mobilities of herbicides [1, 2, 3]. Some studies revealed that sorption of triazines were dependent on most likely organic matter fraction in the soil [1, 2]. Other study showed that organic carbon fraction in carbonate soil was mainly responsible for triazine group herbicide [3]. The impact of organic carbon for the sorption behavior of pesticide has also been observed for other study [4].

In July and August 2021, a serious wildfires burnt 1,700 square kilometres of forest in Turkey's Mediterranean Region. The wildfires started in Manavgat, Antalya Province, on 28 July 2021. Wildfire predominantly had severe effect on vegetation and soil in the area. The objective of this study was to evaluate the impact of wildfires on mobilities of metribuzine herbicide for agricultural soil from Manavgat, Antalya.

2. MATERIALS and METHODS

Soils were obtained from locations from Manavgat Antalya from Turkey. Second soil was taken from the wildfire area to compare the effect of wildfire on herbicide mobility. Soil samples were sieved through 2-mm mesh screen. Chemical and physical features of soils are reported in Table 1. The pH of was analyzed by pH electrode. A particle-size determination of soil was conducted using hydrometer which was given in other study [4]. Total organic carbon of the soil was evaluated by Walkey–Black method [5].

Tablo 1. Physical and chemical properties of soils prior to and after wildfire

Physical and Chemical Properties	Soil 1	Soil 2*
Sand (%)	72	64
Silt (%)	24	31
Clay (%)	4	5
Texture	Sandy Loam	Sandy Loam
Bulk Density, ρ_b(g/cm^3)	1.59	1.63
Porosity	0.48	0.42
pH$_{(1:1)}$	7.8	7.6
Total Organic Carbon, TOC (%)	1.01	0.78

Analytical-grade metribuzine was made in 0.02 M $CaCl_2$. Pentafluorobenzoic acid (PFBA) (Aldrich Chemical Co., Inc.) was used as a non-reactive tracer to identify the hydrodynamic flow behavior in selected soil. The columns were made of plexiglass materials with PTFE caps (10-cm long by 2-cm diameter). Miscible-displacement experiments were performed at two porous media and two different initial metribuzine herbicide concentrations (Co = 20 and 100 mg/L) under saturated flow conditions (Table 2). The columns were fully filled with soil and saturated with water before conducting metribuzine miscible-displacement experiments. Non-reactive tracer PFBA tests were conducted to evaluate flow conditions in selected soils prior to metribuzine flooding. After reaching water saturation condition, PFBA or metribuzine solution was injected into the column until effluent concentration reached initial effluent concentration. After PFBA or metribuzine flooding, water was injected to column to get tracer out of the column. During the miscible-displacement experiments, samples were obtained from the column and analyzed. PFBA and herbicide breakthrough curves were made by drawing relative concentration (C/Co) versus Pore volume

(PV). PFBA and metribuzine were analyzed by UV–Visible spectrophotometer. Measured wavelengths are 254 nm and 233 nm for PFBA and metribuzine, respectively. BTCs of metribuzine and PFBA were analyzed using moment analysis to calculate the retardation factor and mass recoveries for PFBA and metribuzine.

Tablo 2. Experimental conditions for miscible displacement experiments

Solutions	**v (cm/hr)**	**R [ ]**	**Column K_d (L/kg)**	**Mass Recovery (%)**
PFBA	26.0	1.0	0	101.1
20 mg/L Metribuz.	26.0	1.94	0.28	97.4
100 mg/L Metribuz.	26.0	1.91	0.27	98.6
*20 mg/L Metribuz.	26.0	1.48	0.14	99.3
*100 mg/L Metribuz.	26.0	1.46	0.13	99.2

3. RESULTS

Miscible displacement experiments were performed for two various porous media and different metribuzine concentrations (Co=20 and 100 mg/L). Soil samples were represented as prior and after wildfire cases. Experimental conditions and results are given in Table 2. The BTCs for the conservative PFBA exhibit significantly symmetrical for both arrival/elution parts of breakthrough curves. This indicated the absence of retardation (R=1) which was also identified by moment analysis and confirmed the presence of ideal transport conditions in the soil system (Figure 1).

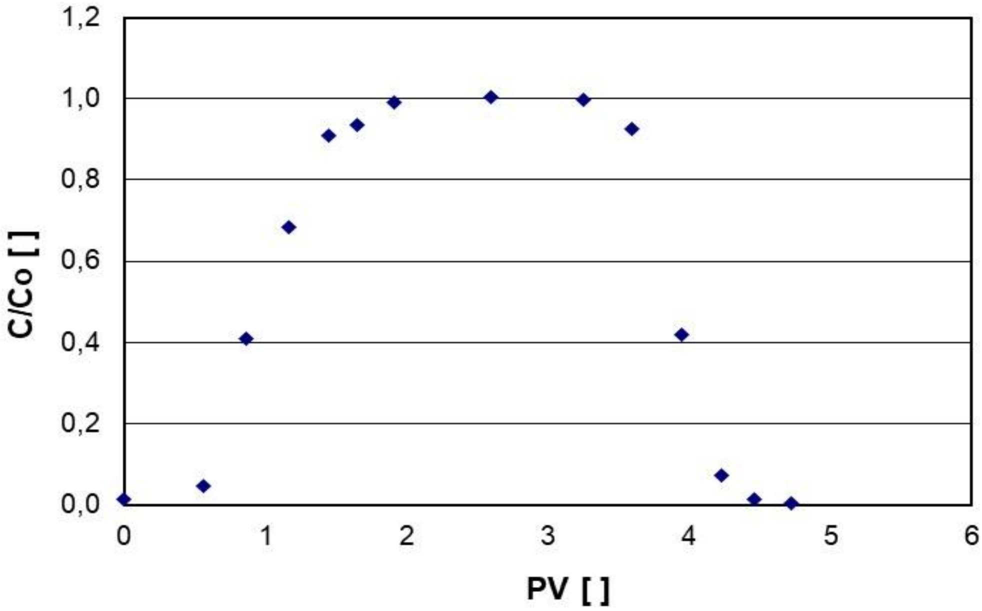

Figure 1. PFBA non-reactive tracer miscible displacement experiment breakthrough curves

Transport of metribuzine predominantly retarded relative to PFBA case in the soil (Fig. 2). K_d values and retardation factors (R) for metribuzine are reported in Table 2. According to the results, two different initial herbicide concentrations had negligible results in terms of retardation factor. This indicated the presence of linear sorption behavior for two different porous media condition (Table 2).

Miscible-displacement studies showed that sorption of metribuzine exhibited linear and rate-limited sorption and desorption parameters that predominantly contributed to the non-ideality for soil. This was identified due to the presence of organic carbon component in soil. The high mass recoveries (> 95%) postulated that transformation or irreversible effect of sorption did not influence the transport of metribuzine in soils. PFBA and metribuzine BTCs for 2 different soil condition and initial metribuzine concentration were reported in Fig 1 and 2. It was also postulated that following wildfire, percent of organic carbon fraction was reduced by 20%, which significantly led to the enhancement of metribuzine mobility in soil. Results indicated that retardation factor and K_d values were similar with other studies conducted in the Region of Mediterranen in Turkey [1, 2, 3, 4]. Organic carbon fraction is directly proportional to retardation fraction and K_d values which was identified by other studies [1, 2, 3, 4, 8, 10].

Metribuzine exhibited non-ideal transport behavior even for conditions prior to and after wildfire. This was due to the presence of organic components for both soils. The effect of organic fraction phenomenon was also observed by other researches that triazine sorption onto carbonate, iron oxide/hydroxide and clay mineral in porous media is negligible and the effect of organic fraction (> 0.1%) was predominant [1, 2, 3, 6]. This effect on non ideal sorption and desorption behavior for organic substances has been extensively studied in previous studies [1, 2, 3, 7, 8, 9, 10].

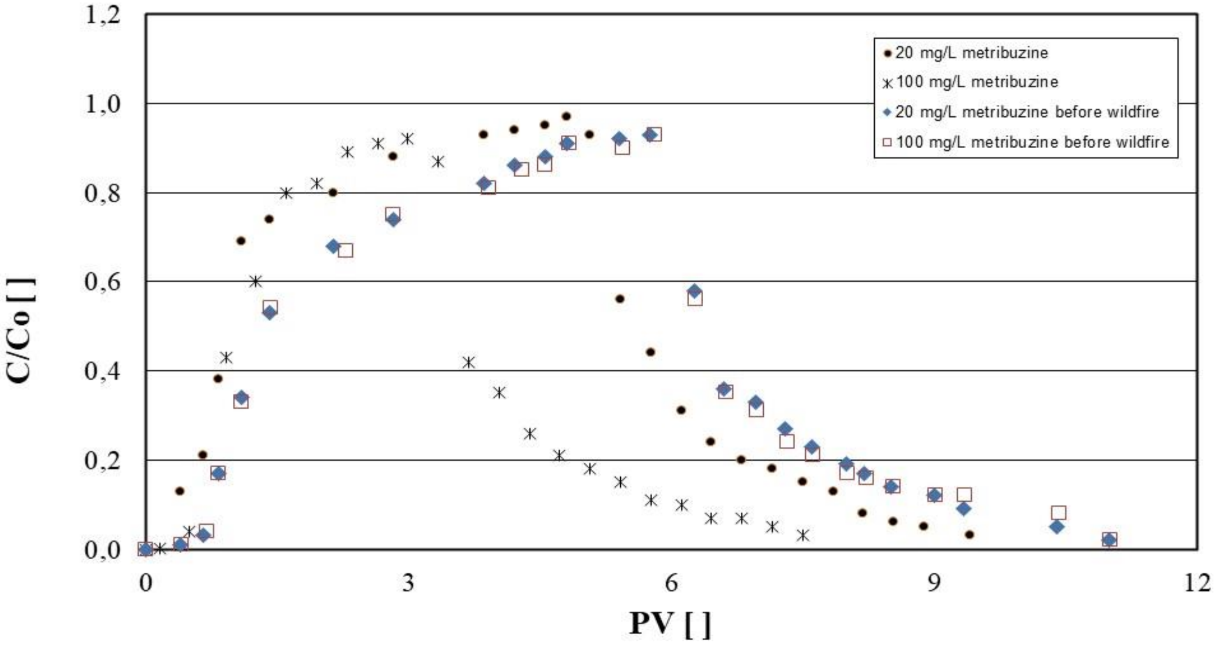

Figure 2. Metribuzine breakthrough curves for soils prior to and after wildfire

4. CONCLUSION

Wildfires are a natural process in many ecosystems, but they are increasing in size, severity, and frequency in many areas. Following the wildfire, loss of vegetation and environment could lead to have differences for the soil properties. Wildfires have a predominant effect on the physical and chemical properties of the soil. Metribuzine has been one of the most used triazine group herbicide which could cause extensive groundwater and soil contamination. The objective of this study was to investigate the effect of wildfires for the fate and transport of atrazine for agricultural soil. Miscible displacement experiments were used for the objectives. Miscible-displacement experiments were conducted for the objectives using 2 different agricultural soils. The calculated distribution coefficient (Kd) from linear sorption isotherm of atrazine was 0.28 and 0.13 L/Kg for soils prior to and after wildfire, respectively. Results indicated that that organic matter fraction of soil has predominantly played major role on sorption of metribuzine and exhibited rate-limited sorption-desorption. As a result, sorption of metribuzine onto soil after wildfire was lower which could lead to more risk for the contamination risk of groundwater resources. The results of this research would also help for the implementation of herbicide management strategies for contaminated sites.

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The author of the paper declare that she complies with the scientific, ethical and quotation rules of ETOXEC in all processes of the paper and that she does not make any falsification on the data collected.

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Research Article

Ecology of *Trifolium elazizense*, an Endemic Alpine Meadow Species from Türkiye

Mustafa KESKİN [1*], Veysel SONAY [2], İbrahim Ertuğrul YALÇIN [3], Volkan ALTAY [4], Münir ÖZTÜRK [5]

Article Info

Corresponding Author e-mail:
trifolium@hotmail.com

Institution: [1] Marmara Unıversity
[2] Harran Unıversity
[3] Bahçeşehir Unıversity
[4] Hatay Mustafa Kemal Unıversity
[5] Ege Unıversity

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ABSTRACT

This study presents some ecological characteristics of *Trifolium elazizense*, a local endemic alpine meadow plant species in the East Anatolian region of Türkiye. Elemental analyses were carried out in plant and soil. Soil-plant relationships were evaluated. The results obtained from all plant parts of *Trifolium elazizense* (root, stem and leaves) showed that the elemental concentrations of boron, calcium, copper, potassium, manganese, lead and zinc were within the limit values; cadmium, iron and magnesium were above the limit values. The general concentration of all elements in the soil samples is generally within acceptable limits.

Türkiye'den Alpinik Çayırlarda Yetişen Endemik *Trifolium elazizense* Türünün Ekolojisi

ÖZET

Bu çalışma, Türkiye'nin Doğu Anadolu bölgesinde lokal endemik, alpin çayır bitkisi olan *Trifolium elazizense* türünün bazı ekolojik özelliklerini sunmaktadır. Toprakta ve bitkide element analizleri yapılmıştır. Toprak-bitki ilişkileri değerlendirilmiştir. *Trifolium elazizense* türünün tüm bitki kısımlarından elde edilen sonuçlar (kök, gövde ve yapraklar) element konsantrasyonlarının bor, kalsiyum, bakır, potasyum, manganez, kurşun ve çinko değerleri sınır değerlerinin; kadmiyum, demir ve magnezyum ise sınır değerlerinin üzerindeydi. Toprak örneklerindeki tüm elementlerin genel konsantrasyonu genel olarak kabul edilebilir sınırlar içindedir.

1. INTRODUCTION

The diversity of plant species in an ecosystem plays an important role in its stability as well as productivity and contributes significantly to the maintenance of ecological functions, especially the continuity of nutrient/water cycles together with the continuation of vital activities [1-9]. For this reason, examining the plant diversity present in different ecosystems and elucidating the ecological relationships with their habitats greatly contributes to the understanding of conservation biology of sensitive plant taxa, particularly the relict, rare and endemic plants found in such ecosystems [10-13].

The variability of microclimatic conditions at different altitudes of mountain ecosystems too is reflected in the diversity of plants, especially endemics, found in such habitats [14]. The reason being in parallel with changes in the altitude factor of mountain ecosystems; these cause significant changes in the existing ecological conditions, especially in climate, plant ecophysiology and soil dynamics [15]. These ecosystems; especially alpine and subalpine ones; play an important role through their different ecological functions [16]. Mountain ecosystems are among the ecological environments characterizing isolated environments, including special areas where sensitive plants such as relict, rare and endemic plants grow. They show different plant diversity [17].

Knowledge about the habitat preferences of endemic plants distributed in restricted areas facilitates the understanding of plant-soil relationships in ecological terms [13]. Türkiye has an important position in terms of eco-genetic resources because of its location at the intersection of biodiversity gene centers of the Middle East and the Mediterranean [13, 18]. The country has a high proportion of endemic plants (nearly 31.12 % of the total flora). The reason is country’s diverse geomorphological, topographical and climatic features as well as a wide range of habitats [19-21]. The list of endemic plant taxa is also given in the floristic studies conducted by some researchers [22-26]. The researchers have conducted studies on the ecological characteristics of some endemic, rare and relict woody, shrub and herbaceous plants of ecologically sensitive importance in Türkiye [4, 13, 27-33].

The genus *Trifolium L*. is one of the largest genera in the family Fabaceae, with approximately 300 species distributed worldwide [34]. This genus is one of the most economically important genera due to its widespread use as fodder and green manure and its ability to fix nitrogen through its roots [35, 36]. It is also recorded as one of the genera with the highest species richness in the Mediterranean basin [37]. The genus is represented by 105 species in Türkiye [38, 39]. Many systematic and morphological studies have been conducted on this genus in Türkiye during the last 2 decades [38-48].

Species richness and composition of flowering plants in grasslands is mainly determined by abiotic factors such as topographic and climatic parameters [3, 49]. Among these factors, the effect of microclimate is regarded as the most important one [49]. The determinants of plant species richness and composition in grasslands are often interrelated and have common effects on plant diversity [49]. In view of this situation there is a general lack of information on the ecology of endemic plant species found in alpine meadows. No detailed ecological study has been conducted on the current status of the naturally distributed endemic *Trifolium elazizense* M. Keskin, Sonay and Balos. The present study is the first of its kind undertaken to understand the ecological characteristics of *T. elazizense*.

2. MATERIALS and METHODS

2.1. Studied species

Trifolium elazizense (Figure 1) is a locally endemic plant species, introduced to the scientific world in 2023 [38]. This endemic species is found in alpine meadows on northern slopes, at altitudes between 2100-2300 m in the East Anatolian region of Türkiye.

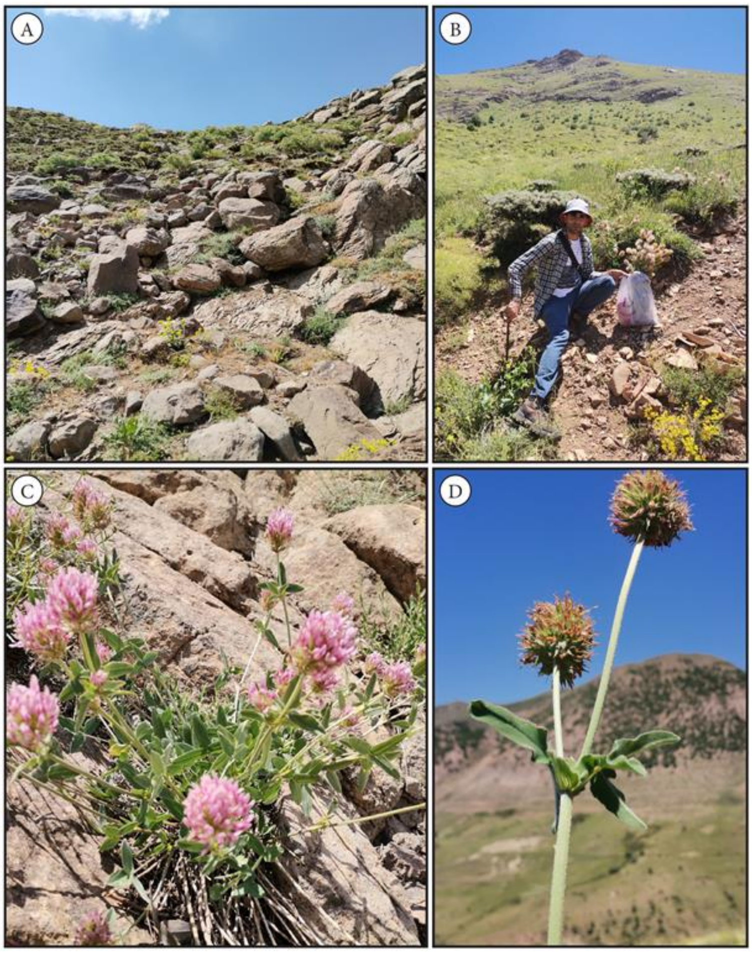

Figure 1: Some photos of the endemic *Trifolium elazizense*
[A The natural habitat of the plant; B Collection of plant samples, researcher V. Sonay; C General view of the plant; D Fruit branches of the plant]

2.2. Study sites

The plant and soil samples were collected from six different sites in the alpine vegetation layer of the East Anatolian region of Türkiye, namely Elazığ-Karakoçan: Sarıcan district, Kejikan highland, northern slopes (2100-2300 m) for the endemic *T. elazizense*.

2.3. Data analysis

Plant samples were separated into leaves, stems and roots. These were individually wrapped in coarse filter paper and labelled accordingly. To inhibit mold growth, all plant materials were oven dried at 80°C for 48 hours at the laboratory to achieve a constant dry weight. Soil samples were placed in glass Petri dishes and oven dried at 80°C for 48 hours. After drying, the samples were sieved through a 2 mm pore diameter steel mesh to remove large particles and prepared for weighing. Both plant and soil samples were accurately weighed in the range of 0.2000-0.2250 grams using an analytical balance (Precisa XB 220A SCS) and transferred to Teflon vessels, designed for microwave digestion system (Berghof - MSW2) [13, 33, 50, 51].

The plant samples were digested with 8 mL of 65 percent nitric acid (HNO_3). In comparison, the soil samples required a more complex digestion protocol consisting of 6 mL of 65 percent HNO_3, 3 mL of 37 percent hydrochloric acid (HCl) and 2 mL of 48 percent hydrofluoric acid (HF). All chemical reagents used were purchased from Merck. After digestion, samples were filtered through Whatman blue band filter paper into sterile 50 mL Falcon tubes using ultrapure water [50]. Following these preparatory steps, elemental analyses for boron (B), calcium (Ca), cadmium (Cd), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), lead (Pb) and zinc (Zn) were performed using inductively coupled plasma optical emission spectrometry (ICP-OES, PerkinElmer - Optima 7000DV) [13, 33, 50, 51].

2.4. Statistical analysis

All elemental concentration calculations were performed using the dry weight of soils, roots, stems and leaves. Statistical analysis for Pearson correlation was performed using IBM SPSS Statistics 25 software. The levels of statistical significance were indicated as **$p < 0.01$ and *$p < 0.05$, and a two-tailed test was used for the analysis [33, 50, 51].

3. RESULTS

The results of the elemental analysis of the plant and soil samples of *T. elazizense* are presented in Table 1.

Tablo 1. Elemental analysis of the plant and soil samples of *Trifolium elazizense*

Elements	**Soil samples** (mg kg^{-1})	**Plant samples**		
		Root (mg kg^{-1})	**Stem** (mg kg^{-1})	**Leaves** (mg kg^{-1})
B	54,738-62,711	15,575-17,134	7,634-8,401	11,155-12,266
Ca	8254,402-9449,931	5138,747-5609,526	2521,858-2752,914	3685,738-4023,415
Cd	0,944-1,234	1,564-1,755	0,793-0,874	1,116-1,229
Cu	43,727-50,230	10,588-11,501	5,208-5,686	7,583-8,245
Fe	5098,975-5837,545	986,513-1076,810	484,133-528,479	707,554-772,339
K	10591,701-12125,766	4196,073-4580,420	2059,243-2247,856	3009,613-3285,307
Mg	2923,619-3347,107	2213,199-2415,915	1086,165-1185,630	1587,406-1732,805
Mn	543,082-621,798	200,583-218,899	98,450-107,441	143,846-156,974
Pb	17,112-19,739	5,700-6,159	2,825-3,031	4,088-4,394
Zn	133,904-153,435	42,077-45,882	20,655-22,527	30,174-32,878

In all plant parts of *T. elazizense* (root, shoot and leaf) the element concentrations of B, Ca, Cu, K, Mn, Pb and Zn were determined to lie within the limit values whereas, Cd, Fe and Mg were above the limit values. The general concentration of all elements in the soil samples is generally within the acceptable limits (Tables 1 and 2).

Tablo 2. Limit values of elements for plant and soil samples [49, 51, 52]

Elements	**Soil samples (min.-max.)** (mg kg^{-1})	**Plant samples (min.-max.)** (mg kg^{-1})
B	20-200	3-90
Ca	7000-15000	3000-30000
Cd	0.06-1.1	0.05-0.5
Cu	25-75	5-30
Fe	5000-50000	50-250
K	5000-25000	1000-50000
Mg	300-8400	100-1000
Mn	10-9000	30-300
Pb	10-40	5-30
Zn	3-300	20-150

Following an evaluation of the concentrations of all elements we found these to be significantly higher in roots than in other parts of the plant (root > leaves > stem). The highest concentrations in plant parts were recorded for Ca; all elements with the highest concentrations generally followed the order Ca > K > Mg > Fe > Mn > Zn > B > Cu > Pb > Cd. Considering the existing concentrations of these elements in the soil samples, the following order was noted K > Ca > Fe > Mg > Mn > Zn > B > Cu > Pb > Cd. The lowest concentration was recorded for Cd in all parts of the plant, as well as in the soil samples. The results obtained in this study revealed that this plant species is able to extract all elements necessary for its growth from the soil where it grows. Similar findings have been reported by Lopes et al. [55] under a similar situation.

An examination of the Pearson correlation coefficients was done between the concentrations of elements in all plant parts (leaves, stem and root) of *T. elazizense* and soil samples taken from its habitat (Table 3), no significant positive or negative correlation was found between Cd and the other elements investigated in this study. On the contrary, a high positive correlation (>0.99, >0.83) was found between all the elements B, Ca, Cu, Fe, K, Mg, Mn, Pb and Zn.

Tablo 3. Pearson's correlation matrix (R) between the elements determined in all the parts of *T. elazizense* and its soil samples

Correlation Matrix (R)									
Pearson Correlation	Ca	Cd	Cu	Fe	K	Mg	Mn	Pb	Zn
B	.907**	-.085	.875**	.898**	.987**	.894**	.898**	.919**	.951**
Ca		.199	.849**	.840**	.947**	.986**	.872**	.965**	.962**
Cd			-.112	-.140	-.009	.358	-.029	-.055	-.067
Cu				.881**	.904**	.882**	.826**	.958**	.939**
Fe					.921**	.868**	.914**	.954**	.917**
K						.927**	.935**	.935**	.978**
Mg							.909**	.907**	.903**
Mn								.984**	.969**
Pb									.886**

***.Correlation is significant at the level of 0.01 (2-tailed).*
**.Correlation is significant at the level of 0.05 (2-tailed).*

Although Pb, like Cd, is a toxic heavy metal for plants, it seems to have a balanced interaction with other macro- and micro-elements and essential heavy metals for plant growth in our plant. However, this balanced interaction does not apply to Cd. This can be explained by the presence of levels in the plant parts (Tables

1 and 2), which indicate that Pb is below toxic thresholds, whereas Cd exceeds toxic levels. No disturbance in the photosynthetic reactions of this endemic plant were found, no delay in flowering and ripening times, no damaged tissues such as necrosis and chlorosis in the leaves. Lack of deficiency of macro and microelements shows that the plant can easily tolerate the toxic metal Cd as a reflection of its ecological adaptation.

4. CONCLUSION

Understanding endemic plants and their habitats from an ecological perspective contributes to their conservation. The results presented here include ecological findings on the local endemic alpine meadow species of Türkiye, *T. elazizense*. This study preliminarily contributes towards elucidation of ecological requirements as well as habitat preferences of *T. elazizense*.

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This study does not require ethics committee permission or any special permission.

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Declaration of research and publication ethics

The authors of the paper declare that we followed the scientific, ethical and citation rules of Environmental Toxicology and Ecology in all processes of the paper and that we did not make any falsification of the data collected. Furthermore, we declare that ETOXEC and its Editorial Board are not responsible for any ethical violations that may have occurred and that this study has not been evaluated in any other academic publication environment than ETOXEC.

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Research Article

Cytotoxic Effects of Biosynthesized Zinc Nanoparticles on Normal Fibroblast Cells and Their Antimicrobial Effect on Pathogenic Strains

Margi PATEL [1*], Farida MINOCHEHERHOMJI [2]

Article Info

Corresponding Author e-mail: **margipatel1411@gmail.com**

Institution: [1] Drs. Kiran & Pallavi Patel Global University
[2] B.P.Baria Science Institute

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ABSTRACT

Nanoparticles, particularly zinc nanoparticles (ZnNPs), have garnered substantial interest in biomedical research for their potential applications in therapeutics and antimicrobial therapy. In this study, we investigated the cytotoxic effects of biosynthesized zinc nanoparticles on normal fibroblast cells and evaluated their antimicrobial efficacy against pathogenic strains. The biosynthesis of zinc nanoparticles was achieved through an eco-friendly and cost-effective approach utilizing biological agents. The cytotoxicity of biosynthesized zinc nanoparticles was assessed on normal fibroblast cells, serving as a model for evaluating biocompatibility. Our results indicate that biosynthesized zinc nanoparticles exhibited minimal cytotoxicity towards normal fibroblast cells, suggesting their potential safety for biomedical applications. Furthermore, the antimicrobial activity of biosynthesized zinc nanoparticles was evaluated against pathogenic strains, including antibiotic-resistant bacteria. The antimicrobial efficacy of zinc nanoparticles demonstrated promising results, highlighting their potential as alternative antimicrobial agents. Overall, this study provides valuable insights into the cytotoxic effects of biosynthesized zinc nanoparticles on normal fibroblast cells and underscores their antimicrobial potential against pathogenic strains, offering opportunities for the development of nanoparticle-based therapeutics and antimicrobial agents in medicine and healthcare.

1. INTRODUCTION

In recent years, the emergence of nanotechnology has revolutionized various fields including medicine and microbiology. Nanoparticles, due to their unique physical and chemical properties, have garnered significant attention in biomedical research for their potential applications in drug delivery, imaging, and antimicrobial therapy. Among these nanoparticles, zinc nanoparticles (ZnNPs) have gained prominence owing to their biocompatibility, low toxicity, and antimicrobial properties [1].

In the context of biomedical research, understanding the cytotoxic effects of nanoparticles on normal cells is crucial to ascertain their safety profile for potential therapeutic use. Fibroblast cells play a pivotal role in tissue repair and maintenance, making them an important model for assessing the biocompatibility of nanoparticles [2]. Thus, investigating the cytotoxic effects of biosynthesized zinc nanoparticles on normal fibroblast cells serves as a fundamental step in evaluating their potential biomedical applications.

Moreover, the antimicrobial properties of zinc nanoparticles have drawn attention as a promising strategy to combat microbial infections [3]. Pathogenic strains of bacteria pose a significant threat to public health due to their increasing resistance to conventional antibiotics. Hence, exploring the antimicrobial efficacy of biosynthesized zinc nanoparticles against these pathogens is imperative for developing alternative antimicrobial agents.

In this study, we aim to investigate the cytotoxic effects of biosynthesized zinc nanoparticles on normal fibroblast cells and evaluate their antimicrobial activity against pathogenic strains. The biosynthesis of zinc nanoparticles offers an eco-friendly and cost-effective approach, utilizing natural resources or biological agents such as plant extracts, fungi, or bacteria. By utilizing biosynthesized zinc nanoparticles, we aim to explore their potential advantages over conventionally synthesized nanoparticles, including enhanced biocompatibility and reduced environmental impact.

Understanding the cytotoxic effects of biosynthesized zinc nanoparticles on normal fibroblast cells will provide valuable insights into their safety profile for biomedical applications. Additionally, assessing their antimicrobial efficacy against pathogenic strains will contribute to the development of novel antimicrobial agents to combat microbial infections.

In summary, this study addresses the dual objectives of assessing the cytotoxic effects of biosynthesized zinc nanoparticles on normal fibroblast cells and evaluating their antimicrobial activity against pathogenic strains. The findings from this investigation hold significant implications for the development of nanoparticle-based therapeutics and antimicrobial agents with potential applications in medicine and healthcare.

In present study, zinc nanoparticles were biosynthesized using green chemistry route and characterized using UV-Vis spectroscopy and Scanning Electron Microscopy. These biosynthesized zinc nanoparticles were tested for antimicrobial activity and bio toxicity assay.

2. MATERIALS and METHODS

2.1. Herbal Plants

Procurement of herbal plants from authentic sources was an extremely important factor in this research. Hence, all herbal plants under evaluation were collected from the botanical garden of Navsari Agriculture University (N.A.U.), Navsari. Botanical identification and authentication was carried out by the authorities of the Herbarium of N.A.U. Plants used for the study are *Mallotus phillipensis*, *Kalanchoe pinnata*, *Syzygium cumini*, *Citrus sinensis*, *Aegle marmelos* and *Flacourtia indica*.

2.2. Bacterial Strains

All bacterial cultures were procured from N.C.I.M., Pune, India. This study included Gram positive bacterial strains, Gram negative bacterial strains and also fungal strains. Bacterial and fungal cultures used in the study are *Staphylococcus aureus* (NCIM 2079), *Escherichia coli* (NCIM 2065), *Pseudomonas aeruginosa* (NCIM 2863), *Salmonella typhi* (NCIM 2501), *Klebsiella pneumonia* (NCIM 2883), *Aspergillus niger* (NCIM 1004) and *Candida albicans* (NCIM 3102).

2.3. Chemicals and Media

DMSO and Methanol were purchased from Finar. Zinc nitrate was procured form Loba Chemie. Nutrient agar, Nutrient broth, Muller Hilton agar, Rose Bengal agar, RPMI 1640/ D-MEM growth medium supplemented with 10% foetal calf, MTT solution were purchased from Hi-Media Laboratories Pvt Ltd (Mumbai, India).

2.4. Synthesis of ZnNPs

The present work was carried out at Department of Microbiology, B. P. Baria Science Institute, Navsari, Gujarat, India. All the plants after their identification were thoroughly washed with water and dried under shade for about ten days. The dried plant samples were ground well into fine powder in a mixture grinder. 10 gm leaves powder of *Flacourtia indica, Syzygium cumini, Citrus sinensis, Mallotus phillipensis, Kalanchoe pinnata* and *Aegle Marmelos* were each mixed with 100 ml organic solvent (methanol) separately in each flask. The mixture was incubated at room temperature for 48-72 hours on rotary shaker. Mixture was filtered using Whatmann Filter Paper No.1 and evaporated in the hot air oven at room temperature to yield the powder form of pure extract. Stock solutions of crude extracts were prepared by mixing organic solvent with appropriate amount of dried extracts to obtain a final concentration of 100 mg/ml. The solvent used was 20% DMSO. The filtrates were collected and stored at 4 ºC for conducting further experimental work related to biosynthesis of nanoparticles.50mL of each leaf extract was taken and boiled to 60-80 ˚C. 5 grams of zinc nitrate was added to the solution as the temperatures reached 60 ˚C. This mixture is then boiled until deep, yellow-colored precipitates are formed and flask was kept overnight at room temperature [4].

2.5. Characterization of ZnNPs

2.5.1. UV Visible Spectral Analysis

Although, color change is an indicator of nanoparticle formation, it cannot be the sole, reliable parameter indicating formation of ZnNPs, hence the shift in the absorption spectra for ZnNPs as observed by UV-Spectrophotometer (Equip-Tronics, EQ-824). The shift in the absorbance spectra indicated the formation of nanoparticles. Distilled water taken as blank.

2.5.2. Scanning Electron Microscopy (SEM)

The SEM analysis was performed at Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, Gujarat, India. Scanning Electron Microscopy (SEM) was done to examine the average particle size and morphology of the ZnNPs. A drop of aqueous solution containing the ZnNPs was placed on the SEM's sample stage. Once vacuum is attained in the sample chamber, the operator then proceeds to align the electron gun in the system to the proper location. The electron gun shoots out a beam of high energy electrons, which travels through a combination of lenses and apertures and eventually hits the sample. As the electron gun continues to shoot electrons at a precise position on the sample, secondary electrons will bounce off the sample. These secondary electrons are identified by the detector. The signal found from the secondary electrons is amplified and sent to the monitor, creating a 3D image.

2.6. Antimicrobial activity by agar diffusion method

Antimicrobial activity were performed at B.P.Baria Science Institute, Navsari, Gujarat, India. Antimicrobial activity of zinc nanoparticles was tested individually against test organisms by Agar Well Diffusion method. Pure cultures were subcultured into sterile nutrient broth and incubated at 37 ºC for 24-48 hours. Each test organism was spread uniformly onto the individual plates using spread plate technique. Wells of 8 mm diameter were made on pre-incubated nutrient agar plates using cup borer. Using sterile micropipette tips, 100 µL of each biosynthesized nanoparticle was pipetted into the above mentioned well in all the plates. After incubation, the diameters of zone of inhibition were measured.

2.7. Bio toxicity Assay

MTT (3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazolium bromide) assay was conducted using a modified method of **Labieniec *et al.* (2003)** and **Lapshina *et al.* (2005) [5,6].** Normal fibroblast cell were used in this assay, it was obtained from extra part of product of conception material at Shree Krushna Gene Lab and Research Center, Rajkot. The normal fibroblast cells were cultivated in RPMI 1640/D-MEM growth medium supplemented with 10% foetal calf. The cells were grown in incubator at 37oC and 5% CO_2.

Confluent cells (70–80%) in Corning flasks were detached using a trypsin solution followed by removing the trypsin. The cells were re-suspended in D-MEM growth medium and counted using a hemacytometer. Cell densities were adjusted to 1x105 cells/mL. The suspension of cells (1000 µL) was seeded into a pre-labeled micro centrifuge tubes. Three set for replica for each concentration of compound used were made. The tubes were incubated at 37°C and 5% CO_2 for 24 hours.

After seeding the cells for 24 hours, the tubes were taken out from the incubator and the cells were exposed with D-MEM growth medium containing test compound and incubated for a further 24 hours at 37°C and 5% CO_2. Each compound was tested in ten different concentrations for the normal fibroblast cells. There after 100 µL of MTT solution (5 mg/ml final concentration) was added to the wells and incubated for 1 hour at 37°C and 5% CO_2. At the end of the treatments, the medium was removed prior to the addition of DMSO (200 µL) into each well. The 24-wells plate was allowed to stand for 10 minutes followed by shaking for 15 seconds. The colour was measured at wavelength 562 nm. The absorbance obtained was used to determine the IC_{50} values. The cytotoxic nature of ZnNPs was calculated using the following formulas [7].

$$\%\ \text{Cell viability} = (\text{Absorbance of test} \div \text{Absorbance of control}) \times 100$$

$$\text{Cytotoxicity} = 100 - \%\ \text{cell viability}$$

3. RESULTS

3.1. Phytochemical Screening

The results of phytochemical tests indicated presence of secondary metabolites in leaf extracts of *Flacourtia indica (Burm. f.) Merr., Syzygium cumini L., Citrus sinensis, Mallotus phillipensis, Kalanchoe pinnata* and *Aegle marmelos* as listed in Table-1. Preliminary phytochemical screening has indicated the presence of alkaloids, tannins, saponins, flavonoids, proteins, steroids and terpenoids in almost all the plant extracts.

Tablo 1. Qualitative phytochemical analysis of methanolic extract of *Flacourtia indica* (Burm. f.) Merr., *Syzygium cumini, Citrus sinensis, Mallotus phillipensis, Kalanchoe pinnata* and *Aegle marmelos*

Sr.N	**Phyto-constituents**	**Results**					
		Flacourtia indica (Burm. f.) Merr.	***Syzygium cumini***	***Citrus sinensis***	***Mallotus phillipensis***	***Kalanchoe pinnata***	***Aegle marmelos***
1	Alkaloids	+	-	+	+	+	+
2	Tannins	+	+	-	+	+	+
3	Saponins	+	+	-	-	+	+
4	Anthraquinones	-	-	-	-	-	-
5	Anthocyanides	+	-	-	-	-	-
6	Phenolic flavonoids	+	+	-	+	+	+
7	Flavonoids	+	+	-	+	+	+
8	Carbohydrates	-	-	-	+	-	-
9	Proteins	+	+	+	+	+	+
10	Steroids	+	+	-	+++	-	-
11	Terpenoids	+	++	-	+	+	+
12	Cardiac glycosides	-	-	-	-	-	-
13	Phlobatannins	-	-	-	-	+	+

3.2. Synthesis of ZnNPs

Various herbal plants have been used for the green synthesis of zinc nanoparticles. Synthesis of ZnNPs is most commonly done by reduction of the zinc nitrate. The possible mechanism involved in the formation of zinc nanoparticles is dependent on the reaction of the zinc ions present in the solution with the polyphenols such as the tannins, glycosides, and flavonoids that are present in the plant extract forming the complexation [8]. Light brown to dark brown colour indicates the formation of zinc nanoparticles in the reaction vessels (Figure 1). Different color change observed in the reaction vessel is due to an effect called Localized Surface Plasmon Resonance.

Figure 1. Biosynthesis of Zinc Nanoparticles. (A) 1mM $ZnNO_3$, Biosynthesis of Zinc nanoparticles, using B) *Kalanchoe pinnata*, C) *Mallotus phillipensis*, D) *Citrus sinensis*, E) *Aegle marmelos, F) Flacourtia indica* and G) *Syzygium cumini* respectively.

3.3. Characterization of ZnNPs

3.3.1. UV-Vis Analysis

Figure 2 represents the UV absorption spectra of zinc nanoparticles biosynthesized using 6 different herbal plants. The absorption peak of the all prepared zinc nanoparticles was found in between 350-410 nm of UV-Vis range.UV-Vis analysis infers that these biosynthesized nanoparticles represent LSPR bands in the visible region. It is related to excitation of electrons present in the metal nanoparticles after their unique interaction with electromagnetic field of light. These excited electrons in plasmonic nanoparticles oscillate collectively to only specific wavelength of light. Therefore, they exhibit selective photon absorption, which can easily be monitored using UV-Vis spectrophotometer [9].

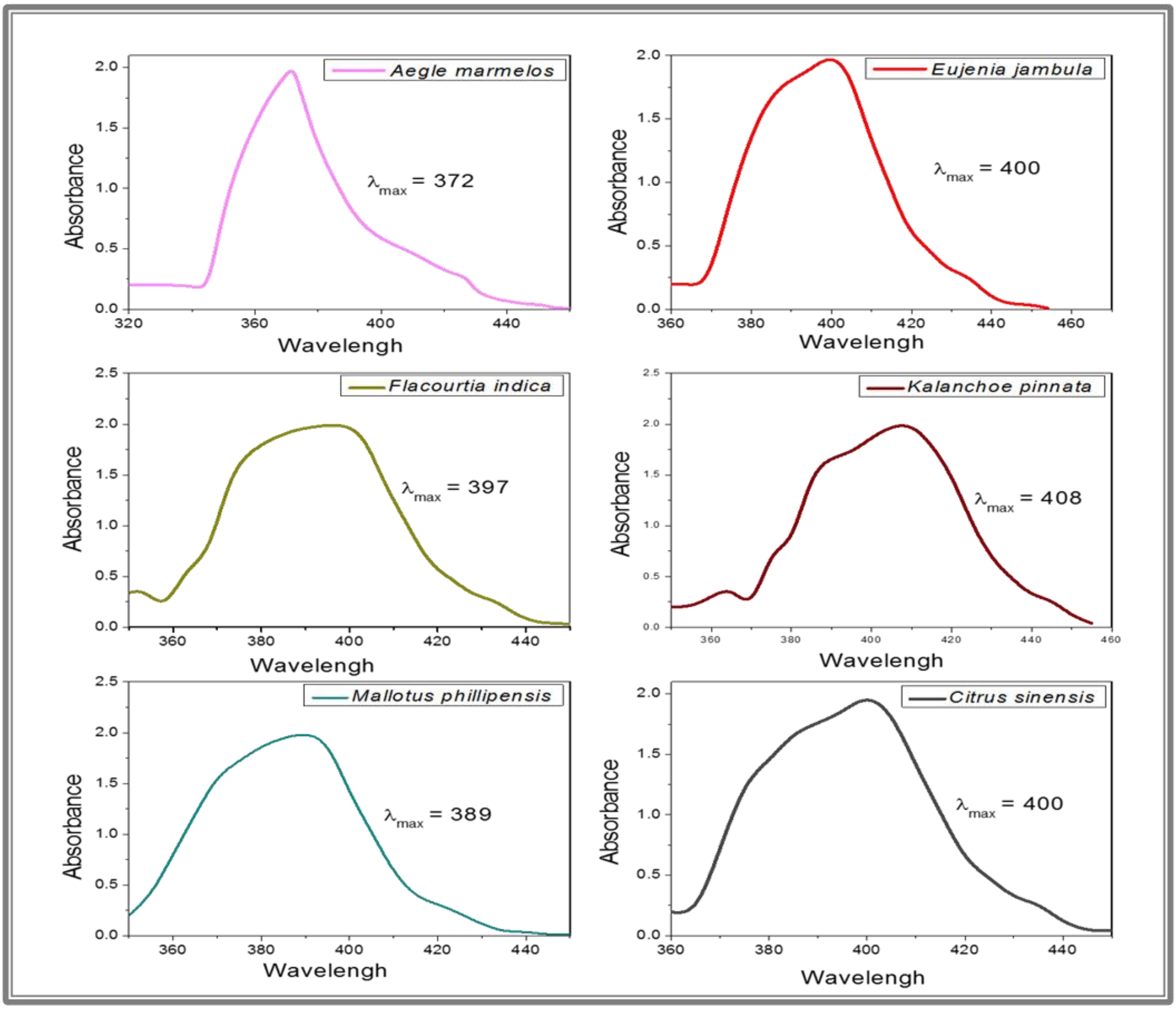

Figure 2. UV-Vis Spectra of zinc nanoparticles prepared using different herbal extracts: *Citrus sinensis*, *Aegle marmelos*, *Mallotus phillipensis*, *Kalanchoe pinnata*, *Flacourtia indica* and *Syzygium cumini*.

The use of different herbal plants in the biosynthesis process can lead to variations in the size, shape, and surface chemistry of the ZnNPs. These factors, in turn, affect the LSPR and the corresponding absorption peak. Plant extracts typically contain various bio molecules like flavonoids, terpenoids, and alkaloids, influencing their optical properties. The unique interaction between the metal nanoparticles and the phytochemicals present in the plant extracts may result in slight variations in the UV-Vis absorption spectra, even though all ZnNPs exhibit LSPR bands within the visible range.

3.3.2. SEM Analysis

The nanoparticles shape and size was characterized by high-resolution scanning electron microscopy. SEM images were seen in 2 µm magnification range, which clearly demonstrated the presence of almost all spherical shaped nanoparticles with average particle size ranging from 65-99 nm (**Figure.3 A-F**).Out of the total six nanoparticles synthesized, zinc nanoparticles synthesized from *Flacourtia indica* has smallest size nanoparticle (~65-72 nm) as compared to others.

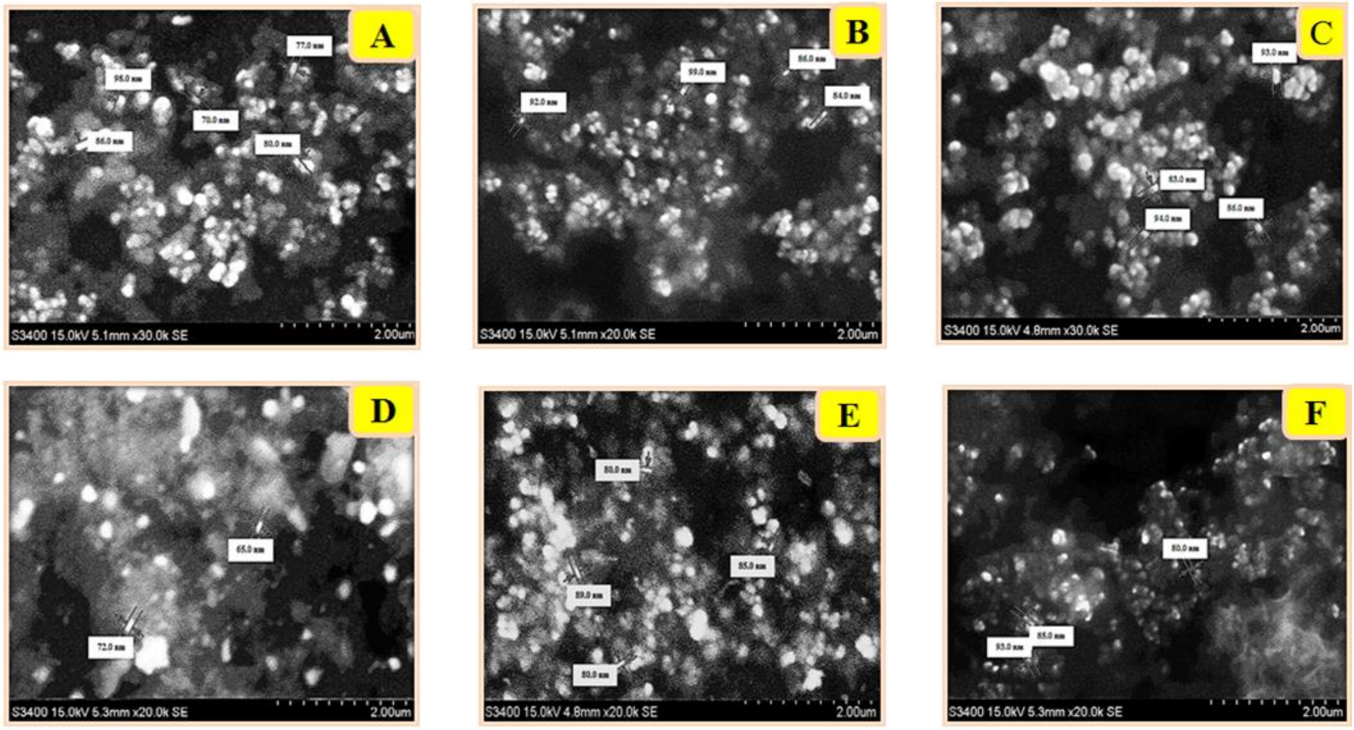

Figure 3. SEM images of zinc nanoparticles prepared using different herbal extracts**,** (A) *Aegle marmelos*, (B) *Citrus sinensis*, (C) *Syzygium cumini*, (D) *Flacourtia indica*, (E) *Mallotus phillipensis*, (F) *Kalanchoe pinnata.*

3.4. Antimicrobial Potency

The biosynthesized zinc nanoparticles from 6 different herbal plants were noticed to be active against fungi than bacteria (Figure 4), thereby exhibiting strong activity and wide antimicrobial action. From the graphical representation (Figure 5), it can be clearly seen that in case of antifungal activity, zinc nanoparticles synthesized from all the six plants showed highest activity against *Aspergillus niger*as well as against *Candida albicans*. Moderate activity was recorded for antibacterial activity against all bacterial strains. Antifungal activity is likely derived through electrostatic attraction between the negatively charged cell membranes of microorganisms and the positively charged nanoparticles [10]. Inhibition zones vary according to types of pathogens involved, synthesis methods applied and concentrations of nanoparticles and size of biosynthesized metal nanoparticles used.

Figure 4. Antimicrobial activity of zinc nanoparticles

In case of *Escherichia coli* and *Klebsiella pneumoniae* lower standard deviation indicates that the zone sizes are relatively consistent across the different plant extracts. Whereas in case of *Aspergillus niger*, *Candida albicans* higher standard deviation suggests more variability in the zone sizes, possibly due to the differing effectiveness of the plant extracts against these strains.

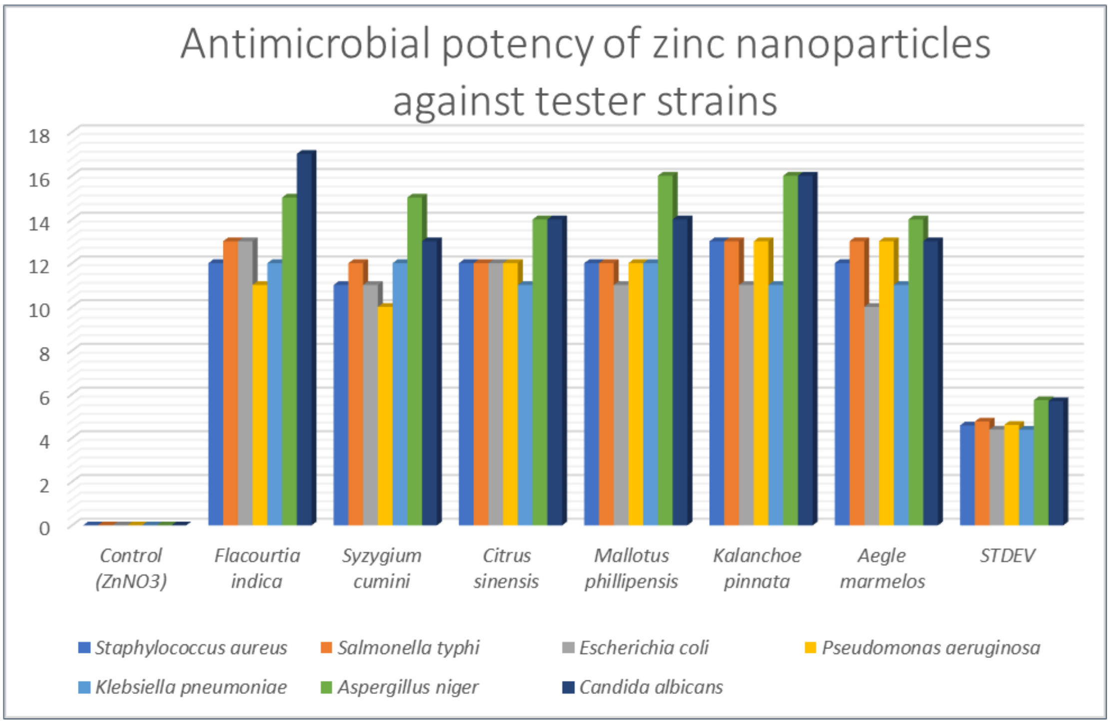

Figure 5. Antimicrobial potency of zinc nanoparticles against tester strains

Tablo 2. Antimicrobial activity of biosynthesized zinc nanoparticles against pathogenic strains with Standard Deviation

Microbial strains Plant extracts	***Staphylococcus aureus***	***Salmonella typhi***	***Escherichia coli***	***Pseudomonas aeruginosa***	***Klebsiella pneumoniae***	***Aspergillus niger***	***Candida albicans***
Control (ZnNO3)	0	0	0	0	0	0	0
Flacourtia indica	12	13	13	11	12	15	17
Syzygium cumini	11	12	11	10	12	15	13
Citrus sinensis	12	12	12	12	11	14	14
Mallotus phillipensis	12	12	11	12	12	16	14
Kalanchoe pinnata	13	13	11	13	11	16	16
Aegle marmelos	12	13	10	13	11	14	13
STDEV	4.5721726	4.75094	4.386125	4.598136	4.375255	5.72796	5.682052

The p-value obtained from the ANOVA test for the given data **(Table.2**) is approximately 0.828. Since the p-value is much greater than the common significance level of 0.05, there is no statistically significant difference in the inhibition zones among the different plant extracts for the various microbial strains. This suggests that the plant extracts do not differ significantly in their effects on the microbial strains tested.

3.5. Bio toxicity Assay

MTT assay was performed on normal cells. Here in this study as mentioned earlier, normal fibroblast cellswere chosen. The small size and the relatively large surface area of nanoparticles resulted in increased toxicity when compared to particles in micrometer size. Therefore, the present study was carried out with objective to evaluate the toxic potential of biosynthesized zinc nanoparticles on exposure to normal fibroblast cells [11]. The cytotoxicity of zinc nanoparticles was initially investigated by measuring the cellular activity. The results of the MTT viability assay showed that zinc nanoparticles have significant toxic effect as per used different concentrations (0.125 µL to 100 µL) on normal fibroblast cells.

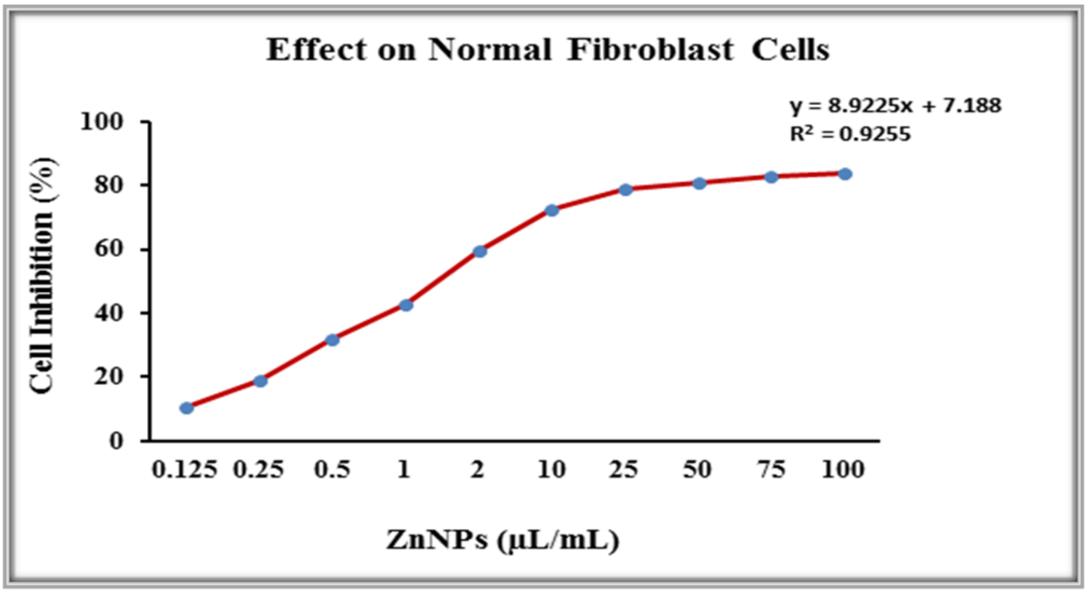

Figure 6. Effect of zinc nanoparticles on cell viability

However, the IC_{50} values were calculated from a regression curve (Figure.6).These values represent the effective concentration of copper nanoparticles that decreases the amount of viable cells to 50% after 24 hours. Values of IC_{50} obtained by MTT assay resulted to be higher for normal fibroblast cells (4.79 µL/mL). In the present study, exposure of zinc nanoparticles caused concentration dependent cytotoxicity as revealed by cell viability assay.

4. DISCUSSION

The green synthesis of zinc nanoparticles (ZnNPs) using plant extracts is an eco-friendly and sustainable approach that has garnered significant attention in recent years. The method utilizes the rich phytochemical content of plants, particularly polyphenols like tannins, glycosides, and flavonoids, which act as both reducing and stabilizing agents during nanoparticle synthesis. The mechanism underlying the formation of ZnNPs is largely attributed to the reduction of zinc ions (Zn^{2+}) in the presence of these bioactive compounds, resulting in the formation of zinc nanoparticles.

The process of ZnNP formation begins with the reduction of zinc nitrate, a common precursor, in the presence of plant extracts. According to Solabomi *et al.* (2019), the interaction between zinc ions and polyphenols is critical, leading to the complexation that ultimately results in the formation of nanoparticles [8]. Polyphenols play a dual role; they not only reduce Zn^{2+} to Zn^0 but also stabilize the newly formed nanoparticles, preventing their aggregation. This mechanism has been supported by several other studies. Sharmila *et al.* (2019) reported the successful synthesis of ZnNPs using *Tecoma castanifolia* leaf extract, highlighting the role of quercetin, a potent flavonoid, in reducing Zn^{2+} and forming stable nanoparticles [12].

The color change observed during the synthesis, from light brown to dark brown, is an important visual indicator of nanoparticle formation. This color change is associated with a phenomenon known as Localized Surface Plasmon Resonance (LSPR), which occurs due to the collective oscillation of electrons on the surface of the metal nanoparticles when excited by light at specific wavelengths. Other studies have also observed similar UV-Vis absorption patterns, corroborating the findings related to LSPR. Supriya and kumari (2019), synthesized AgNPs using Aloe vera extract and observed an absorption peak at around 430 nm, consistent with the LSPR effect [13]. This observation was similar to the results obtained using other plant extracts, reinforcing the role of LSPR as a fundamental property of metallic nanoparticles.

The smaller size of ZnNPs synthesized using *Flacourtia indica* (~65-72 nm) can be attributed to the specific phytochemicals present in the extract, such as polyphenols, flavonoids, and tannins. These compounds not only reduce zinc ions but also act as capping agents, stabilizing the nanoparticles and limiting their growth, which results in smaller sizes. A recent study by Kumar et al. (2022) demonstrated that ZnNPs synthesized using *Azadirachta indica* (Neem) had sizes ranging from 75-85 nm, with the phytochemical composition of the extract being a key factor in determining the nanoparticle size [14]. For instance, smaller ZnNPs have been shown to possess enhanced antibacterial properties due to their ability to interact more effectively with microbial cells.

Moreover, in vitro antibacterial and antifungal activities of ZnO nanoparticles have been widely reported [15,16]. Green synthesized ZnO NP using *Beta vulgaris, Cinnamomum tamala, Parthenium hysterophoru*, orange fruit extract showed strong inhibition against *Escherichia coli, Klebsiella pneumoniae, Staphylococcus aureus, Candida albicans, Aspergillus niger, Botrytis cinerea, Penicillium expansum* etc. [17, 16, 18, 19, 20]. Similarly, our study highlighted the antibacterial and antifungal potential of green synthesized ZnNPs against different bacterial strains i.e., *Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa*, *Salmonella typhi*, *Klebsiella pneumonia* and fungal strains *Aspergillus niger* and *Candida albicans* (Table: 2)

The cytotoxic effects observed in your study can be attributed to the small size of the nanoparticles, which increases their surface area relative to volume, thereby enhancing their interaction with cellular components. This increased surface area allows for greater reactivity, which can lead to higher levels of oxidative stress, membrane damage, and ultimately, cell death. A study by Chen *et al*. (2019) supports these findings, showing Size-dependent cytotoxicity study of ZnO nanoparticles in HepG2 cells [21]. Zinc nanoparticles (ZnNPs) hold significant potential in cancer therapy due to their unique physicochemical properties, including small size, large surface area, and ability to generate reactive oxygen species (ROS). However, further research needs to optimize their design, improve targeting efficiency, and ensure safety in clinical applications, ZnNPs could become a valuable tool in the fight against cancer.

4. CONCLUSIONS

Total six different herbal plants were used to biosynthesize zinc nanoparticles. All of the zinc nanoparticles biosynthesized during the current study showed potent biological activities against all microbial tester strains. Out of the total six nanoparticles synthesized, zinc nanoparticles synthesized from *Flacourtia indica* was chosen for bio-toxicity assay due smallest size nanoparticle (~65-72 nm) as compared to others. Zinc nanoparticle has significant toxic effect as per used different concentrations on normal fibroblast cells. Therefore, our results concluded that sensitivity towards nanoparticle exposure is depends on the concentration of nanoparticles.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

Author's Contribution

The authors contributed equally to the study

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

Declaration of research and publication ethics

The authors of the paper declare that we followed the scientific, ethical and citation rules of Environmental Toxicology and Ecology in all processes of the paper and that we did not make any falsification of the data collected. Furthermore, we declare that ETOXEC and its Editorial Board are not responsible for any ethical violations that may have occurred and that this study has not been evaluated in any other academic publication environment than ETOXEC.

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Review Article

Toxic-Free Environment: Forever Chemicals Removal from Water and Wastewater

Nada A A JARADAT [1*], Yüksel Orhan ARDALI [2]

Article Info

Corresponding Author e-mail:
nadajaradat95@gmail.com

Institution: [1] Ondokuz Mayıs Unıversıty
[2] Ondokuz Mayıs Unıversıty, Faculty of Engıneerıng

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS), commonly known as "forever chemicals," are persistent synthetic compounds that have been widely utilized since the mid-20th century across various industries. Due to their environmental persistence and potential health risks, PFAS has become a significant concern, particularly in relation to water and wastewater contamination. This paper investigates the complex challenges associated with PFAS, focusing on existing regulatory frameworks, treatment strategies, and innovative clean technologies that aim to reduce or eliminate these harmful substances. The study emphasizes the importance of advanced treatment methods such as electrochemical degradation, nanofiltration, adsorption, and biodegradation, each offering varying degrees of success. Despite advancements in treatment technologies, prevention remains the most effective strategy to minimize PFAS pollution. The paper calls for collaborative efforts from regulatory bodies, industries, and communities to implement more sustainable practices, ensuring a toxic-free environment and aligning with circular economy principles. Continuous research and international cooperation are crucial for developing effective long-term solutions to address PFAS contamination and safeguard both public health and the environment.

1. INTRODUCTION

Forever chemicals, per- and polyfluoroalkyl substances (PFAS) are persistent organic pollutants of industrial origin. PFAS are known for their resilience, ability to accumulate in nature, and potential toxicity. These compounds are characterized as non-biodegradable, non-reactive, non-photolytic, and hydrolysis-resistant, rendering them recalcitrant in the environment [1,2]. Two of the most prominent PFAS compounds, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), have been widely detected in various environmental matrices, including drinking water, surface water, groundwater, and costal water, raising significant public health and environmental concerns [3]. These chemicals are categorized by their carbon-chain length, with "long-chain" and "short-chain" distinctions [4,5]. While the extensive use of poly- and perfluoroalkyl substances (PFAS) has a history dating back to the 1950s, it was only in the early 2000s, subsequent to the initial reports indicating the presence of PFAS in both wildlife and human serum, that scientific inquiries into their properties, occurrence, environmental fate, and health effects began to gain substantial momentum [6]. Over the past few decades, the prevalence of PFAS has become increasingly apparent, with their extensive detection across diverse environmental compartments. Nakayama et al. [7] underscore this widespread occurrence, characterizing PFAS as widely distributed in nearly all aquatic matrices, encompassing drinking water, surface water, groundwater, and coastal water [3,7].

A comprehensive understanding of the physicochemical properties of PFAS is crucial for predicting their environmental behavior and transport mechanisms. The melting and boiling points of these compounds determine whether they exist as solids, liquids, or gases under standard conditions [8]. Most PFAS are typically found in solid form, either crystalline or powdery, at atmospheric pressure. However, shorter-chain PFAS, with carbon chain lengths between 4 and 6, are more likely to be liquids. For example, the melting point of perfluorobutanesulfonic acid (PFBS) is -21°C, while perfluorooctanoic acid (PFOA) has a melting range of 45°C to 54°C [9]. The density of liquid-phase PFAS at ambient temperatures affects their environmental dynamics [10,11]. To date, only a handful of well-characterized PFAS compounds, including perfluorinated carboxylic acids (PFCAs), perfluorooctane sulfonate (PFOS), and fluorotelomer alcohols, have experimentally determined water solubility data [10].

The long-lasting nature of forever chemicals raises concerns about their environmental and health impacts. PFAS are linked to health risks, ranging from acute to chronic conditions. Studies have reported potential links between PFAS exposure and thyroid disorders, asthma, anxiety, obesity, pediatric allergies, hyperuricemia, peroxisome proliferation, immune toxicity, kidney disorders, liver damage, cancer, immune system dysfunction, developmental disorders, and cardiovascular diseases [12-14]. Recent studies have also revealed their presence in food products, contributing to concerns about dietary exposure. Human exposure occurs through various sources, such as contaminated food, drinking water, inhalation of air and dust, and PFAS-containing products [3,15,16]. While some long-chain PFAS have faced restrictions, the production of short-chain PFAS and alternative variants has increased. Furthermore, examinations of PFAS have expanded to encompass their effects on animal health. Research, as demonstrated by Poothong et al. [17] and Rand et al. [18], reveals toxic outcomes, encompassing immunotoxicity, carcinogenicity, and hormonal disorders. These effects are notably linked to perfluoroalkyl carboxylic acids (PFCAs) in animals.

In response to growing concerns, regulatory agencies such as the U.S. Environmental Protection Agency (EPA) have established health-based guidelines for PFAS concentrations in drinking water [19], The EPA has set a lifetime health advisory level of 70 ng/L for the combined concentrations of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), and lower guidelines for short-chain PFAS C4–C7 range from 300 to 7,000 ng/L. However, there is increasing pressure for stricter regulations as the understanding of PFAS toxicity evolves.

The challenge of removing PFAS from water has become a critical focus for wastewater treatment plants (WWTPs), which are significant sources of PFAS contamination in aquatic environments, with industrial wastewater often having higher PFAS concentrations than domestic wastewater [20-27]. The removal of PFAS in WWTPs depends on influent concentrations [28], treatment processes [27], PFAS characteristics, and the proportion of industrial wastewater [20,29]. PFAS can also enter the environment through atmospheric emissions [30] and the use of PFAS-contaminated sludge as fertilizer [31]. Extensive research has been conducted on PFAS in WWTP effluent and recipient waters [22,23,25,32].

The multifaceted aspects of per- and polyfluoroalkyl substances (PFAS) in the environment are comprehensively investigated in this paper. With a particular focus on regulatory frameworks, treatment strategies, clean technologies, and their potential integration into a circular economy, with a specific emphasis on the promotion of a toxic-free environment and alignment with the principles of the Green Deal.

2. PFAS AND THE GREEN DEAL FOR A TOXIC-FREE ENVIRONMENT

The European Green Deal is a comprehensive plan to make the European Union's economy sustainable and to achieve a toxic-free environment. The strategy is the first step towards a zero pollution ambition for a toxic-free environment. The European Green Deal and the toxic-free environment initiative concerning per- and polyfluoroalkyl substances (PFAS) are focused on diminishing the usage and exposure of these persistent chemicals across different products and processes. The 2020 Chemicals Strategy for Sustainability (CSS) identifies PFAS as a pressing concern necessitating immediate action, with the European Union (EU) actively working to restrict their use in fire-fighting foams. Aligned with the overarching goals of the Green Deal, which seeks climate neutrality and pollution reduction, there is an emphasis on addressing PFAS pollution. Despite these efforts, concerns have been raised about the EU potentially deviating from its commitment to banning non-essential hazardous chemicals, including PFAS, due to industry influence. The EU's regulatory framework, shaped by the European Green Deal, employs a comprehensive strategy involving risk assessment, management, and mitigation strategies. This includes the establishment of maximum allowable limits for PFAS in various environmental compartments, backed by rigorous scientific assessments incorporating evidence from research studies and monitoring programs evaluating PFAS occurrence and behavior in diverse environmental matrices [33, 34].

In February 2023, the Environmental Protection Agencies of Denmark, Sweden, Norway, Germany, and the Netherlands submitted a proposal to the European Chemical Agency (ECHA) advocating for a ban on the use of per- and polyfluoroalkyl substances (PFAS) [35]. This proposal was driven by recent evidence indicating significant issues with the transition to PFAS alternatives, resulting in widespread environmental contamination. Denmark led the way as the first country to ban PFAS, and now other EU nations are backing restrictions on these chemicals due to their carcinogenic, endocrine-disrupting, and immunotoxic properties. This proposal is one of the most comprehensive plans received by the ECHA in the past 50 years [36].

Regulatory agencies and researchers have intensified efforts to understand the sources, behavior, and pathways of PFAS in the environment [38, 39]. The release of PFAS into the environment occurs through multiple pathways. Diffuse sources such as atmospheric deposition and surface run-off contribute to environmental contamination [40, 41]. Other pathways include emissions from landfills [42, 43], discharge from wastewater treatment plants (WWTPs) [23, 44], and contamination from firefighter training facilities

[24, 45]. As a result, PFAS are ubiquitously present in the environment, even in sparsely populated regions [46, 47].

Table 1. Industry sectors and usage categories for PFAS, with subcategories indicated in parentheses [37].

Industry branches	
Aerospace Industry (7)	Mining Sector (3)
Biotechnology Sector (2)	Nuclear Industry
Construction and Building Sector (5)	Oil and Gas Industry (7)
Chemical Industry (8)	Pharmaceutical sector
Electrolysis and Plating Industry	Photographic Sector (2)
Electroplating Industry (2)	Plastics and Rubber Production (7)
Electronics Sector (5)	Semiconductor Industry (12)
Energy sector (10)	Textile Manufacturing (2)
Food industry	Watch-making industry
Machinery and Equipment Manufacturing	Woodworking Industry (3)
Metal Products Manufacturing (6)	

PFAS substances have found extensive use in both industrial and consumer products, owing to their distinctive attributes such as water and grease resistance. Historically, PFAS have been integral to a wide array of applications and products, including non-stick cookware, where they have been employed to create non-stick coatings, notably Teflon. They have also been instrumental in rendering fabrics stain and water-resistant, as seen in waterproof clothing, carpets, and upholstery [48]. In food packaging, PFAS have been utilized in items such as fast-food wrappers, microwave popcorn bags, and pizza boxes to prevent oil and grease penetration. Firefighting foams, featuring PFAS components like perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), have been employed to combat liquid fuel fires. Furthermore, PFAS have played a role in the electronics industry, particularly in the manufacturing of semiconductors and printed circuit boards, as well as in hydraulic fluids for their lubrication properties [48]. These compounds have even made their way into cosmetics and personal care products for their water-resistant qualities. Additionally, the medical field has harnessed PFAS, notably in manufacturing certain medical devices, including catheters and tubing, to improve their biocompatibility and durability Furthermore, the chemical industry has utilized PFAS in various industrial processes, including the production of fluoropolymers and other chemicals [49], Table 1 provides a list of industry sectors and additional areas of application where PFAS have been or are currently in use [37].

However, it is essential to highlight that growing concerns regarding the environmental persistence and potential health risks associated with PFAS have prompted increased scrutiny and regulation across these applications. Consequently, concerted efforts are underway to reduce PFAS usage in certain products and to explore safer alternatives. Furthermore, several countries and regions have imposed restrictions and bans on specific PFAS compounds [4, 5, 30].

3. REGULATIONS AND FRAMEWORKS

The regulatory frameworks for PFAS in water and wastewater vary worldwide, with more stringent guidelines and standards being established in developed countries. The European Green Deal and the toxic-free environment approach aim to reduce the exposure to PFAS and other hazardous substances. In Turkey, specific regulations and standards for PFAS removal from wastewater and water are not well-defined, but there is a growing concern about the presence of PFAS in drinking water sources [19].

The regulatory frameworks for PFAS in water and wastewater can be summarized as follows:

Global: The United States Environmental Protection Agency [19] exercises broad enforcement discretion, allowing for potential exemptions for Publicly Owned Treatment Works (POTW) facilities. Nevertheless, it encourages states and municipalities to proactively identify known or suspected sources of PFAS and employ best management practices to address potential PFAS discharge [19].

Europe: The European Chemicals Agency (ECHA) has issued a proposal to restrict PFAS in various products, including textiles [19].The European Green Deal and the toxic-free environment approach aim to reduce the exposure to PFAS and other hazardous substances, promoting environmental sustainability and reducing pollution [50]. On June 13, 2017, the European Union formally implemented Regulation (EU) No. 2017/1000, as published in the Official Journal. This regulatory measure delineates restrictions concerning perfluorooctanoic acid (PFOA), its salts, and related substances. The amendment introduced a novel entry, denoted as entry 68, to Annex XVII of the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) framework [33].

Turkey: Turkey introduced regulations on persistent organic pollutants, specifically focusing on substances like Perfluorooctane sulfonic acid and its derivatives (PFOS). Effective from November 14, 2018, the law prohibits the manufacture, market entry, and use of PFOS, emphasizing the reduction of emissions and proper waste management. The regulations mirror several provisions of the EU legislation but have distinct aspects. Notably, Turkey listed PFOS, along with other chemicals, imposing strict limits on their presence in substances, mixtures, articles, or parts thereof. The legislation demonstrates Turkey's commitment to addressing environmental concerns associated with PFOS, aligning with global efforts to regulate these persistent and harmful substances [50, 51].

Enhancements in PFAS removal technologies are required to optimize their efficiency and feasibility. The imperative lies in the establishment of regulatory compliances, coupled with the essential components of exposure assessment and risk characterization, to provide precautionary guidance about water source protection and the security of water supply.

4. IMPLEMENTING CIRCULAR ECONOMY FOR EFFECTIVE PFAS REDUCTION IN THE ENVIRONMENT USING BEST AVAILABLE TECHNIQUES

The circular economy, an emerging economic model committed to eliminating waste and pollution through the strategic design of products, holds significant promise for addressing the challenges posed by per- and polyfluoroalkyl substances (PFAS) in wastewater [52, 53]. Integrating the principles of Best Available Techniques [54] [54] for PFAS reduction, this approach emphasizes material recovery and reduction [54, 55]. Research consistently demonstrates that the circular economy can effectively curtail the extraction of primary resources, reducing the demand for raw materials and potentially diminishing the presence of PFAS in the environment [56].

Within the context of PFAS removal, the circular economy, along with Best Available Techniques [54], contributes to mitigation efforts in several ways:

Preventive Product Design: Aligning with the preventive principle, the circular economy discourages the production of PFAS-containing products. The promotion of designs and manufacturing processes free from PFAS and other hazardous substances directly reduces the potential environmental burden associated with PFAS release [57, 58].

Integrating Green Raw Materials: Green raw material in the circular economy is a clean technology for minimizing PFAS. This aligns with circular economy principles, reducing contamination risk and promoting sustainability. Applying the "keeping products in use" principle to these materials minimizes environmental impact and resource demand. Furthermore, adopting green raw materials supports natural system regeneration [59].

Advancements in PFAS Recovery and Recycling: Fostering progress in the recovery and recycling of PFAS from used products, the circular economy minimizes the environmental impact of discarded PFAS-containing items. This approach also mitigates the risk of PFAS entering landfills or being incinerated, thereby averting potential secondary environmental contamination [60].

Exploration of New Applications for Recycled PFAS: Encouraging the exploration of new applications for recycled PFAS, the circular economy stimulates market demand. This economic model creates a viable demand for recycled PFAS, rendering the recycling process more economically feasible. This transition towards a circular approach in PFAS management not only addresses environmental concerns but also establishes a foundation for sustainable economic practices in the domain of PFAS remediation [61].

Regenerative Natural Systems: The circular economy principle of regenerating natural systems aligns with the goal of avoiding the use of non-renewable resources and preserving or enhancing renewable ones, which can contribute to reducing the demand for PFAS and other non-renewable substances [62].

Sludge Management: Within the urban water cycle, the circular economy can help reduce the problems associated with PFAS in sludge, thereby minimizing the environmental impact of these substances [63].

These integrated strategies collectively position the circular economy, integrated with BAT, as a promising and comprehensive strategy for effectively addressing PFAS challenges in wastewater and the environment.

5. FOREVER CHEMICALS REMOVAL FROM WATER AND WASTEWATER

Addressing the removal of per- and polyfluoroalkyl substances (PFAS) from wastewater is imperative due to its potential consequences for future generations. Successful PFAS removal within wastewater treatment plants relies upon diverse factors, encompassing operational considerations, specific parameters of the wastewater treatment process, and the nature of the wastewater source [64]. An economically viable, environmentally sustainable, and operationally uncomplicated solution for PFAS removal from wastewater lies in the implementation of biological methods [49]. Additionally, an innovative approach involves harnessing naturally occurring microbial degradation pathways, presenting a promising methodology for the comprehensive elimination of PFAS contamination [65].

Long-chain per- and polyfluoroalkyl substances (PFAS) exhibit greater bioaccumulation and persistence, coupled with increased toxicity compared to their shorter-chain counterparts, owing to their stronger affinity for proteins and other biological molecules. Degradation of long-chain PFAS can lead to the formation of shorter-chain PFAS through various mechanisms, including biodegradation, abiotic degradation (facilitated by factors like sunlight and ozone), and advanced oxidation processes (AOPs) in water treatment. Although these processes may produce shorter-chain PFAS as intermediates, their effectiveness varies, with AOPs being efficient but costly and energy-intensive [54, 66, 67].

Conventional wastewater treatment methods often fall short of eliminating PFAS effectively, leading to the discharge of undegraded PFAS into the environment. It is crucial to acknowledge that the produced shorter-chain PFAS intermediates may retain toxicity levels similar to or even exceeding those of the original long-chain PFAS, emphasizing the importance of comprehensive removal strategies for both long-chain and shorter-chain PFAS in wastewater [67, 68]. Currently, researchers are exploring new and clean PFAS removal technologies, aiming to eliminate PFAS effectively instead of merely capturing and storing them. The recent technologies for PFAS removal from contaminated water and wastewater are as follows:

5.1. Adsorption

5.1.1. Activated carbon

The removal of per- and polyfluoroalkyl substances (PFAS) from water and wastewater is a critical environmental concern due to their persistence and potential health risks. Activated carbon has been widely utilized as an effective method for PFAS removal, although it has limitations in terms of efficiency for short-chain PFAS compounds and energy-intensive regeneration processes [62]. In recent years, researchers have conducted several experimental trials using granular activated carbon (GAC) to examine the effects of different PFAS attributes, such as isomer structure, functional groups, and perfluorocarbon chain length, on the elimination of various PFAS compounds [69, 70]. The findings indicate that GAC demonstrated removal efficiencies averaging between approximately 80% and 90% for PFAS [71, 72].

Cantoni et al. investigated PFAS adsorption in tap water using various activated carbon types, validated by full-scale plant data. Results showed AC's removal efficiency varied with surface charge, pore size, and competition with dissolved organic matter. Findings were confirmed at full scale, revealing removal variations among PFAS compounds [73]. Park et al. explored PFAS breakthrough in groundwater’s using fixed-bed adsorbers and RSSCTs with four activated carbons. Results showed that PFAS breakthrough was influenced by compound hydrophobicity and carbon characteristics [8]. M.G. Kibambe et al. [74] examined the effectiveness of wastewater treatment processes for reducing perfluoroalkyl substances (PFASs), with a particular emphasis on perfluorooctane sulfonate (PFOS) removal via adsorption. Their research assessed the efficiency of various treatment methods, with a specific focus on adsorption as a key PFOS removal process. The findings underscored the potential of adsorption as a highly effective method for PFOS reduction, showcasing its ability to selectively capture and remove PFOS from wastewater, thereby offering a promising solution for mitigating PFAS contamination [74]. Riegel et al. [75] explored removing short-chain PFAS during drinking water treatment using activated carbon and ion exchange. Short-chain PFAS were effectively removed by activated carbon over short run times, while longer PFAS required longer durations [75]. In a water utility, Burkhardt et al. conducted pilot research in two phases: first analyzing nine PFAS compounds, then sixteen. Both phases utilized five different GACs, employing pore and surface diffusion models to predict outcomes [76]. The study showed GAC effectively removed all tested PFAS. However, remediation effectiveness varied significantly between the phases, conducted at different times of the year, indicating fluctuating PFAS adsorption properties. Granular activated carbon (GAC) proved to be an efficient remediation method for PFAS removal in this pilot study, meeting the utility's treatment objectives [76].

5.1.2. Biochar

Biochar, a carbonaceous material derived from the thermal decomposition of biomass through pyrolysis, has emerged as a promising avenue for addressing the contamination of water and wastewater by polyfluoroalkyl substances (PFAS) [77]. Its efficiency in PFAS removal stems from its unique physical, chemical, and biological properties, which are influenced by the composition of the original biomass used in its production. These properties include surface area, porosity, pH, functional groups, and surface charge, all of which play pivotal roles in the adsorption and degradation mechanisms involved in PFAS removal. The diverse nature of biochar, owing to variations in feedstock and pyrolysis conditions, poses a challenge in defining it by a single characteristic. However, this diversity also offers opportunities for tailored biochar formulations optimized for specific PFAS removal applications, thus contributing to the advancement of sustainable and effective wastewater treatment technologies [78, 79].

Wu et al. [80] tested the adsorption of perfluorocanoic acid (PFO) by engineered biochar made from three different feedstocks: switchgrass [29], water oaks leaves (WO), and biosolid (BS). The adsorption mechanisms, thermodynamic analysis, and the impact of factors such as pH, salinity, and organic matter were investigated. The biochar was engineered with additives of $FeCl_3$ and carbon nanotube (CNTs) to enhance PFOA adsorption, with biosolid biochar demonstrating better PFOA adsorption due to its higher contents of O% and S% as well as higher metal contents such as Ca, Cu, and Fe. Among the engineered biochars investigated, BS-Fe displayed the highest maximum adsorption capacity for PFOA at 469.65 µmol/g, while WO-CNT exhibited the lowest adsorption potential with 39.54 µmol/g. The sorption behavior of PFAS with chain lengths ranging from 4 to 11 fluorinated carbons was investigated by Fabregat-Palau et al. [81] across various carbon-rich materials, such as biochars, compost, charcoal fines, and activated carbon. The study revealed a correlation between an increase in sorption and the length of the PFAS chain, highlighting the significance of hydrophobic interactions as the primary driving force behind PFAS sorption. Emphasis was placed on the crucial role of the CORG/O molar ratio and the specific surface area (SSA) of the material as key properties influencing this sorption process. Furthermore, the research underscored the potential of biochars as an environmentally sustainable alternative to activated carbon for PFAS removal, demonstrating promising results in terms of sorption efficiency. Militao et al. [82] examined the efficiency of alginate-encapsulated plant albumin and rice straw-derived biochar in removing PFAS from water. Their study demonstrated high removal efficiency, with up to 99% for PFOS and 39% for PFBS. Particularly, the non-thermal (NT) biochar variant outperformed prior natural material-based adsorbents. The research emphasized the pH-independent nature of biochar-alginate beads and their resilience to natural organic matter.

5.1.3. Ion Exchange Resin

Ion exchange resins have been widely used for the removal of per- and polyfluoroalkyl substances (PFAS) from wastewater. These resins, including cationic exchange resins [46] and anion exchange resins, have shown effectiveness in removing positively charged contaminants and negatively charged PFAS from water sources [83]. The use of ion exchange resins for PFAS removal involves a regeneration process using an organic solvent and brine solution to treat the resin and remove PFOS and PFOA from the water [84]. Anion exchange resins, in particular, have been highlighted in various studies for their efficacy in PFAS removal, with some studies providing estimated cost curves for their implementation [85]. Adsorption using ion exchange resins has demonstrated significant promise, achieving removal efficiencies of ≥99% for PFAS as well as dissolved organics (>90%) [86, 87]. However, it's important to note that results obtained at high initial concentrations (5–1000 mg/L) of PFAS in synthetic and spiked wastewaters may not directly translate to lower and more realistic concentrations (<1000 ng/L). Additionally, the documented formation of nitrosamine precursors during the regeneration of amine-based anion exchange (IX) resins poses a notable concern [88]. Deng et al. evaluated different anion exchange resins for the removal of perfluorooctane sulfonate (PFOS) from simulated wastewater, providing insights into the sorption behavior and mechanism of PFOS on these resins [89]. Woodard et al.studied the use of ion exchange resin for PFAS removal, showing consistent results between virgin and regenerated resin loading cycles [84]. Zeidabadi et al. proposed an integrated approach combining ion exchange and electrochemical technologies for managing PFAS exhausted ion-exchange resins, showing enhanced regeneration efficacy with the presence of methanol but reduced electrochemical decomposition of PFAS [90]. Further research is needed to optimize the use of ion exchange resins for the removal of per- and polyfluoroalkyl substances (PFAS) and other pollutants to improve water treatment processes [91].

5.2. Membrane Technologies

High-pressure membrane processes such as reverse osmosis (RO) and Nanofiltration (NF) membranes are most effective for removing various classes of trace organic compounds from water [92]. Several studies have investigated the efficiency of membrane technologies for PFAS removal from water and wastewater, demonstrating significant variation based on the type of membrane used and the specific PFAS compounds targeted. Tang et al. [93] found that reverse osmosis (RO) membranes achieved over 99% removal of long-chain PFAS like PFOA and PFOS, although short-chain PFAS were less effectively removed. Similarly, Steinle-Darling and Reinhard [94] showed that RO membranes could remove over 90% of PFOA and PFOS, but highlighted that membrane fouling could affect performance. Nanofiltration (NF) membranes have also shown promise; in a study by Thompson et al. [95], NF membranes achieved 95% removal of long-chain PFAS but had reduced efficiency for shorter chains. A study by Guo et al. [96] also confirmed these findings, noting that NF membranes effectively removed PFOS with a rejection rate exceeding 90%. Forward osmosis (FO) has been explored as well, with Boo et al. [97] reporting that FO membranes could reject up to 98% of PFAS, though performance was influenced by membrane orientation and draw solution composition. Additionally, ultrafiltration (UF) combined with activated carbon adsorption was shown by Rahman et al. [11] to enhance PFAS removal, particularly for long-chain compounds, though UF alone was insufficient. Schäfer et al. [98] further corroborated these findings, showing that combined membrane systems could achieve over 99% removal for some PFAS, but emphasized the need for hybrid approaches to address short-chain variants effectively. These studies collectively suggest that membrane technologies, particularly RO and NF, are highly effective for removing long-chain PFAS. However, very little data are available regarding the use of membranes in the removal of short-chain PFAS [99, 100]. Generally, nanofiltration (NF) membranes demonstrate high rejection rates—often exceeding 95%—for molecules with molecular weights greater than 150 Da, which includes many short-chain PFAS [101]. Research by Zeng et al. [102] indicated that lowering the pH enhances the membrane's ability to reject short-chain PFAS, underscoring the significance of pH in the rejection process. Additionally, the ionic strength can influence the extent of Donnan exclusion, affecting how membranes reject negatively charged PFAS. Organic fouling, which forms a layer on the membrane surface, also impacts PFAS rejection efficiency. Like ion exchange methods, membrane technologies do not destroy PFAS but instead produce a concentrated brine solution that requires further treatment or disposal. [103].

5.3. Electrochemical Degradation

Electrochemical degradation has shown significant potential for PFAS removal from water and wastewater, with numerous studies assessing its effectiveness. Zhuo et al. [104] investigated the use of boron-doped diamond (BDD) electrodes for degrading PFOA, achieving over 95% removal within 2 hours, demonstrating the efficiency of BDD electrodes for long-chain PFAS. Shi et al. [105] utilized Ti/Pt electrodes to target PFOS, achieving over 85% removal within 3 hours, showing the method's effectiveness for shorter-chain PFAS. Niu et al. [106] explored PbO2 electrodes and reported up to 90% removal of both PFOA and PFOS, with PFOA being more readily removed. Singh et al. [107] used Ti/IrO2 electrodes and achieved up to 95% removal of PFOS, indicating the potential of these electrodes in wastewater treatment. Yu et al. [108] demonstrated that Fe/N co-doped graphene-modified cathodes in an electro-Fenton process achieved over 90% PFOA removal. The enhanced degradation was due to increased hydroxyl radical production, showing the effectiveness of electrode modification in PFAS treatment.

Further research by Yang et al. [109] employed electrochemical advanced oxidation processes (EAOPs) with stainless steel anodes, achieving approximately 80% removal of PFOS and PFOA, and highlighting the need for process optimization. Adeniji et al. [110] achieved up to 90% removal of PFOA using diamond-like carbon (DLC) electrodes, reflecting their potential for PFAS treatment. Jean et al. [111] combined electrochemical oxidation with UV irradiation, achieving over 95% removal of both PFOS and PFOA, suggesting that integrating methods can enhance treatment efficiency. Pillai et al. [112] used Ti/RuO2 electrodes and achieved up to 89% removal of PFOS, supporting the effectiveness of metal oxide electrodes. Liwara et al. [113] explored the use of palladium on carbon (Pd/C) catalysts, achieving up to 85% removal of short-chain PFAS, highlighting the potential of catalytic electrochemical processes. Additional research by Zhang et al. [114] focused on copper electrodes for PFAS removal, reporting up to 87% removal of PFOS. Yang et al. [115] evaluated nickel-based electrodes and achieved around 82% removal of PFOA, demonstrating another effective approach for PFAS degradation. Collectively, these studies illustrate the diverse effectiveness of electrochemical methods in degrading PFAS, though optimization of electrode materials and treatment conditions remains crucial.

5.4. Biodegradation and Biological Methods

Biodegradation and biological methods have emerged as promising approaches for the removal of PFAS from wastewater. These methods leverage microbial and enzymatic processes to degrade PFAS compounds, offering potential advantages in terms of cost-effectiveness and environmental sustainability. One of the key studies in this area is by Xu et al. [116], examined how PFOA and PFOS affect soil microbial communities, finding that these contaminants significantly reduce microbial diversity and disrupt key soil processes. Higher concentrations of PFOA and PFOS caused greater changes, highlighting the need for careful monitoring of PFAS in soil. Similarly, Smith et al. [117] review innovative treatment technologies for PFAS-contaminated water, specifically foam partitioning and electrochemical methods. Foam partitioning achieved up to 95% removal of PFAS from water, while electrochemical techniques demonstrated up to 90% degradation of PFAS. The study highlights these methods' effectiveness and potential for improving PFAS remediation. A more recent study by Torres-Farradá et al. [118] investigated the potential of white-rot fungi, specifically focusing on the enzyme laccase, for the degradation of per- and polyfluoroalkyl substances (PFAS), particularly PFOA and PFOS. Their study demonstrated that laccase could effectively degrade these compounds, achieving removal rates of 75% for PFOA and 70% for PFOS over a period of 15 days. This research highlights the promise of using fungal enzymes in bioremediation efforts to address the environmental challenges posed by persistent pollutants like PFAS. Tow et al. [119] evaluated the performance of a hybrid biological and chemical treatment system, combining microbial degradation with advanced oxidation processes, which resulted in up to 90% removal of PFOA.

The potential of using engineered bacteria was highlighted by Berhanu et al. [120] who developed a recombinant E. coli strain engineered to express PFAS-degrading enzymes. This genetically modified strain was able to degrade 85% of PFOS within 7 days, demonstrating the potential of genetic engineering to enhance the biodegradation of PFAS. By introducing specific genes encoding PFAS-degrading enzymes into E. coli, the researchers were able to significantly improve the degradation rate compared to unmodified bacteria. Shahsavari et al. [121] investigated the use of activated sludge systems for PFAS removal, achieving up to 70% reduction in PFOS concentrations through optimized microbial activity.

In another study, Grgas et al. [122] examined the use of anaerobic digestion processes for PFAS removal. They reported up to 60% reduction of PFOA and PFOS through the application of specialized anaerobic bacteria. Similarly, Smith et al. [123] explored biological methods for PFAS removal in wastewater treatment, demonstrating that certain microbial communities could degrade up to 70% of specific PFAS compounds under optimized conditions. The study highlighted the integration of these biological processes into existing wastewater treatment plants, suggesting that coupling them with foam partitioning techniques could enhance overall PFAS removal efficiency. These findings indicate the potential for biologically based strategies to contribute to more sustainable PFAS remediation efforts. Further research by Zhou et al. [124] reviewed the biodegradation of PFAS, revealing that while complete mineralization is challenging, specific microbial strains can partially degrade shorter-chain PFAS compounds. The review emphasizes that although biodegradation alone may not achieve full PFAS removal, integrating these biological processes with other treatment technologies could significantly enhance overall remediation efficiency in wastewater systems. Bacteria such as Pseudomonas aeruginosa have also been studied extensively. For instance, Chetverikov et al. [125] examined the biodegradation potential of C_7-C_{10} perfluorocarboxylic acids by a new strain of Pseudomonas mosselii. The study demonstrated that this strain could degrade up to 60% of these PFAS compounds under optimal conditions. The genomic analysis revealed specific enzymes responsible for breaking down the carbon-fluorine bonds, offering insights into the mechanisms of PFAS biodegradation. These findings suggest that Pseudomonas mosselii could be a promising candidate for biological PFAS remediation in wastewater treatment. Collectively, these studies underscore the effectiveness of various biological and biodegradation methods for PFAS removal, though further research is needed to optimize these processes and address challenges such as degradation of short-chain PFAS and overall treatment efficiency.

4. CONCLUSIONS

The pervasive environmental and health risks posed by per- and polyfluoroalkyl substances (PFAS) demand an urgent and comprehensive response. The persistence of these synthetic chemicals, coupled with their widespread use, has resulted in significant contamination, particularly in aquatic environments. The technological advancements reviewed in this study—electrochemical degradation, nanofiltration, adsorption, and biodegradation—offer promising avenues for PFAS mitigation. However, the complexity and cost of these methods often limit their practical application, and none can yet be considered a panacea. The most effective long-term strategy lies in the prevention of PFAS emissions at their source. This requires stringent regulatory controls on the production and use of PFAS, alongside robust efforts to develop and commercialize non-toxic alternatives. Such preventive measures not only reduce the burden on treatment technologies but also align with the principles of a circular economy, where resource efficiency and waste minimization are prioritized.

Transitioning to a circular economy is particularly pertinent, as it presents a systemic approach to reducing environmental contaminants, including PFAS. However, this transition is far from straightforward. It necessitates coordinated action across multiple sectors, including policy reform, industrial innovation, and shifts in consumer behavior. The global nature of PFAS contamination also calls for international collaboration, as unilateral actions are insufficient to address a problem of this magnitude. Collaborative efforts between regulatory agencies, industries, academic researchers, and the public are essential. Regulatory frameworks must evolve in response to new scientific findings, and industries must be held accountable for environmental stewardship. Public engagement and education are critical in driving demand for safer products and supporting policy initiatives aimed at reducing PFAS exposure. Ongoing research is vital to further elucidate the behavior and impact of PFAS in the environment. The development of more sustainable, cost-effective treatment technologies is imperative, as is the investigation of natural attenuation processes and the potential for microbial degradation of PFAS. Future studies should focus on understanding the long-term environmental and health impacts of PFAS, particularly as they relate to cumulative exposure and low-dose effects.

In conclusion, a multifaceted approach that integrates prevention, advanced treatment technologies, regulatory oversight, and public awareness offers the most viable pathway to mitigating the impact of these persistent pollutants. The goal of a toxic-free environment, though ambitious, is achievable with sustained effort and international cooperation, ensuring the protection of both human health and the natural world for future generations.

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The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

Declaration of research and publication ethics

The authors of the paper declare that we followed the scientific, ethical and citation rules of Environmental Toxicology and Ecology in all processes of the paper and that we did not make any falsification of the data collected. Furthermore, we declare that ETOXEC and its Editorial Board are not responsible for any ethical violations that may have occurred and that this study has not been evaluated in any other academic publication environment than ETOXEC.

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