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Makine Öğrenmesi Tabanlı Yaklaşım ile NMC Lityum-İyon Pillerin Geri Dönüşümünde Liç Koşullarının Modellenmesi

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Özet

Bu çalışmada, NMC tipi ($LiNi_xMn_yCo_zO_2$) lityum-iyon pillerin hidrometalurjik yöntemle geri dönüşümünde liç parametrelerinin etkisi, makine öğrenmesi tabanlı modellerle incelenmiştir. Literatürden derlenen 269 deneysel veri noktasından oluşan veri seti, süre, sıcaklık, katı/sıvı oranı, H_2O_2 oranı ve sitrik asit konsantrasyonu gibi temel değişkenleri içermektedir. Lityum (Li) ile geçiş metallerinin (Co, Ni, Mn) çözünme oranları hedef değişken olarak kullanılmıştır. Modelleme sürecinde Doğrusal Regresyon, Karar Ağacı ve Rastgele Orman algoritmaları karşılaştırılmış; en yüksek doğruluk Rastgele Orman modelinde elde edilmiştir ($R^2 > 0.88$). Model çıktıları, SHAP (SHapley Additive Explanations) analizi ile yorumlanarak değişkenlerin önem derecesi belirlenmiş, PDP (Partial Dependence Plot) grafikleri ile de parametrelerin çözünme davranışına etkileri görselleştirilmiştir. Bulgular, sıcaklık ve süre gibi işlem koşullarının özellikle Li çözünürlüğü üzerinde belirleyici olduğunu, H_2O_2 ve sitrik asit konsantrasyonunun ise daha çok geçiş metallerinin çözünmesini etkilediğini göstermiştir. Bu çalışma, literatürdeki verilerin yapay zeka ile yeniden değerlendirilerek deneysel optimizasyona yön verilmesinin mümkün olduğunu ortaya koymaktadır.

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A Machine Learning-Based Approach for Modeling Leaching Conditions in the Recycling of NMC Lithium-Ion Batteries

Abstract

In this study, the effects of leaching parameters on the hydrometallurgical recycling of NMC-type ($LiNi_xMn_yCo_zO_2$) lithium-ion batteries were investigated using machine learning-based models. The dataset, compiled from the literature, consists of 269 experimental data points and includes key variables such as time, temperature, solid-to-liquid (S/L) ratio, H_2O_2 concentration, and citric acid concentration. The dissolution rates of lithium (Li) and transition metals (Co, Ni, Mn) were used as target variables. Linear Regression, Decision Tree, and Random Forest algorithms were compared during the modeling process, with the Random Forest model achieving the highest accuracy ($R^2 > 0.88$). Model outputs were interpreted using SHAP (SHapley Additive Explanations) analysis to determine the relative importance of the variables, and Partial Dependence Plots (PDPs) were used to visualize the effects of process parameters on leaching behavior. The findings revealed that operational conditions such as temperature and time were particularly decisive for Li dissolution, while H_2O_2 and citric acid concentrations had a greater influence on the dissolution of transition metals. This study demonstrates that re-evaluating literature data through artificial intelligence can effectively guide experimental optimization efforts.

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1. Giriş

Son yıllarda elektrikli araçlar, taşınabilir elektronik cihazlar ve enerji depolama sistemlerindeki hızlı gelişmeler, lityum-iyon pillerin küresel üretim ve tüketiminde önemli bir artışa yol açmıştır. Bu artışla birlikte, kullanılmış Li-iyon pillerin oluşturduğu çevresel yük ve değerli metal kaybı da ciddi bir sorun haline gelmiştir (Fan ve ark., 2020). Özellikle NMC ($LiNi_xMn_\gamma Co\_zO_2$) tipi katotlara sahip piller, lityum (Li), kobalt (Co), nikel (Ni) ve mangan (Mn) gibi kritik metalleri içermeleri nedeniyle geri dönüşüm açısından yüksek ekonomik ve çevresel değere sahiptir (Celep ve ark., 2023; Yu ve ark., 2024).

Doğrudan fiziksel ayırma (Diekmann ve ark., 2017), pirometalurjik (Holzer ve ark., 2021), biyoteknolojik (Bahaloo-Horeh and Mousavi, 2017) ve hidrometalurjik (Lv ve ark., 2020) yöntemler olmak üzere çeşitli teknolojilerle bu metallerin geri kazanımı mümkündür. Bu yöntemler arasında hidrometalurji; yüksek saflıkta ürün eldesi, seçici çözünürlük, düşük enerji tüketimi ve daha az zararlı emisyon avantajları nedeniyle öne çıkmaktadır (Fahimi ve ark., 2022). Ancak hidrometalurjik süreçlerin optimize edilmesi, çok sayıda parametrenin bir arada değerlendirilmesini gerektirmekte ve bu durum geleneksel deneysel yöntemlerle zaman alıcı ve maliyetli olmaktadır.

Son dönemde bilimsel çalışmalarda giderek artan şekilde yer bulan makine öğrenmesi (ML) algoritmaları (Acilar, 2020; Musabeyoglu ve ark., 2024), bu gibi çok parametreli süreçlerde etkin modelleme ve öngörü sunma potansiyeli taşımaktadır. ML uygulamaları, yalnızca karmaşık etkileşimleri anlamlandırmakla kalmayıp, aynı zamanda deneysel tasarımlara yön vererek sürecin verimliliğini artırabilir (Niu ve ark., 2025).

Bu çalışmada, literatürden derlenen kapsamlı deneysel verilere dayanarak, NMC tipi Li-iyon pillerin hidrometalurjik geri dönüşümünde kullanılan liç parametrelerinin makine öğrenmesi ile modellenmesi amaçlanmaktadır. Farklı regresyon modelleri karşılaştırılarak en uygun model belirlenmiş, SHAP ve PDP analizleri ile değişkenlerin etkisi yorumlanmıştır.

2. Materyal ve Yöntem

2.1. Asit seçimi ve veri setinin oluşturulması

Bu çalışmada kullanılan veri seti, lityum-iyon pillerin hidrometalurjik liç yoluyla geri dönüşümüne odaklanan bilimsel literatürden derlenmiştir. İlk olarak, bu alandaki 116 akademik makale sistematik biçimde taranmış; yalnızca liç yöntemi içeren ve NMC katotlarıyla yapılan çalışmalara odaklanılmıştır. Literatüre bakıldığında sülfürik asit ve sitrik asidin bu pillerdeki değerli metalleri çözmek için en sık kullanılan asitler olduğu tespit edilmiştir. Bu asitleri kullanan ve yöntem ve parametre benzerliği taşıyan 11 makaleden süre, sıcaklık, katı/sıvı (K/S) oranı, H_2O_2 oranı, asit türü ve asit yoğunluğu gibi temel liç parametreleri ile Li, Co, Ni ve Mn çözünme oranlarını içeren, 179'u sitrik asit, 90'ı sülfürik aside ait, toplam 269 veri toplanmıştır. Makalelerdeki veriler doğrudan tablolar yoluyla veya grafiklerden WebPlotDigitizer yazılımı kullanılarak çıkarılmıştır. Bu çalışmada kullanılan veri seti, literatürde yer alan deneysel çalışmalardan doğrudan derlenmiş olup herhangi bir normalize etme, standartlaştırma ya da aykırı değer temizleme işlemi uygulanmadan kullanılmıştır. Bu tercih, modelin ham veriler üzerinde genel eğilimleri yakalama yeteneğini değerlendirmek ve gerçek dünya verilerine dayalı bir yaklaşım geliştirmek amacıyla yapılmıştır. Sitrik asit; hem literatürde en sık kullanılan asitlerden birisi olması hem de elimizdeki en fazla veriye sahip olması nedeniyle hedef asit olarak seçilmiştir.

2.2. Metal çözünme korelasyonunun incelenmesi

Modelleme öncesinde, hedef metaller (Li, Co, Ni, Mn) arasındaki çözünme ilişkilerinin anlaşılması amacıyla Pearson korelasyon analizi uygulanmıştır. Bu analiz, birden fazla hedef

değişkenin benzer ya da farklı çözünme davranışları gösterip göstermediğini belirlemek amacıyla gerçekleştirilmiştir. Korelasyon matrisleri, modelleme stratejisinin (örneğin, hedeflerin gruplanması) oluşturulmasına yön vermiştir.

2.3. Regresyon modellerinin uygulanması

Elde edilen veri seti üzerinde üç farklı regresyon algoritması uygulanmıştır: Doğrusal Regresyon (Linear Regression), Karar Ağacı (Decision Tree Regressor) ve Rastgele Orman (Random Forest Regressor). Modelleme süreci Python programlama dili kullanılarak, yaygın olarak kullanılan scikit-learn kütüphanesi aracılığıyla gerçekleştirilmiştir. Modeller, veri setindeki bağımsız değişkenler ile hedef değişkenler (Li ve geçiş metallerinin liç verimleri) arasındaki ilişkileri temsil etme yeteneklerine göre değerlendirilmiştir.

Model performansları karşılaştırılırken üç temel değerlendirme metriği kullanılmıştır: R^2 (determinasyon katsayısı), MAE (Ortalama Mutlak Hata) ve RMSE (Kök Ortalama Kare Hatası). Tüm algoritmalarda hiperparametreler, algoritmaların varsayılan ayarları kullanılarak belirlenmiştir; bu sayede modellerin temel performansları karşılaştırmalı olarak gözlemlenmiştir.

Bu analizler, liç sürecindeki deneysel parametrelerin hedef çıktılar üzerindeki etkilerinin en doğru şekilde hangi model tarafından temsil edildiğini belirlemek amacıyla yapılmıştır.

2.4. SHAP ve PDP analizleri

Modelin daha derinlemesine anlaşılması amacıyla, Rastgele Orman algoritması ile eğitilen modelin çıktıları SHAP (SHapley Additive exPlanations) analizi ile yorumlanmıştır. SHAP değerleri, her bir giriş değişkeninin model tahmini üzerindeki katkısını pozitif veya negatif yönde göstererek, değişken etkilerini açıklamaya yardımcı olur.

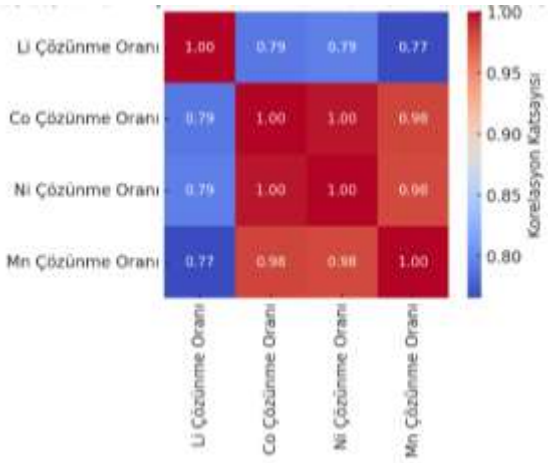
Buna ek olarak, PDP (Partial Dependence Plots) grafikleri kullanılarak, her bir bağımsız değişkenin hedef değişken üzerindeki ortalama etkisi görselleştirilmiştir. Bu grafikler, deneysel tasarım sürecine rehberlik edecek şekilde parametrelerin etkilerini sade biçimde ortaya koymuştur.

3. Bulgular ve Tartışma

3.1. Metal çözünme oranları arasındaki korelasyonun belirlenmesi

Regrasyon modelleme yapılmadan önce Li, Co, Ni ve Mn çözünme oranları arasındaki korelasyon incelenmiştir. Şekil 1'de verilen korelasyon matrisinde görüldüğü gibi Co, Ni ve Mn metalleri için ikili korelasyon değerlerinin 1'e yakın olması bu metallerin çözünme davranışlarının çok benzer olduğunu gösterir. Bu değer Li ve diğer metaller için daha düşük olup 0,77-0,79 aralığındadır. Bu da lityumun daha farklı davranış sergilediğini göstermektedir. Bu yüzden analizlerde Li ayrı bir grup ve Co, Ni ve Mn (geçiş metalleri, GM) ayrı bir grup olarak incelenmiştir.

Literatürde yer alan bazı çalışmalarda (Niu ve ark., 2023), Li, Co, Ni ve Mn metallerinin leaching verimleri arasında yüksek korelasyon bildirilmiştir. Bu durum, kullanılan geniş parametre aralığı (25 farklı asit tipi, çok sayıda deneysel koşul) nedeniyle tüm metallerin benzer koşullarda çözünmesini sağlamış olabilir. Oysa bu çalışmada sadece sitrik asit kullanılmış olup, Li'nin farklı çözünme davranışı belirgin şekilde gözlemlenmiştir. Ayrıca korelasyon analizinde Pearson yöntemi tercih edilmiş, bu da yalnızca doğrusal ilişkileri değerlendirmiştir. Farklı korelasyon yöntemlerinin (ör. Spearman) kullanılması, benzer veri setlerinde farklı sonuçlar ortaya koyabilir.



Şekil 1. Farklı metallerin çözünme oranlarının korelasyon katsayıları

3.2. Verilerin modellenmesi ve model performanslarının karşılaştırılması

Verilerin analizi için farklı modeller denenmiş ve veri setini en iyi açıklayan model seçilmiştir. Uygulanan Doğrusal (Linear), Rastgele Orman (Random Forest) ve Karar Ağacı (Decision Tree) regresyonların karşılaştırması Tablo 1'de yapılmıştır.

Tablo 1. Farklı regrasyon modellere ait ölçütler

Model	Li			GM		
	R^2	MAE	RMSE	R^2	MAE	RMSE
Doğrusal (Linear)	0,678	11,46	14,602	0,688	11,349	14,447
Rastgele Orman (Random Forest)	0,883	6,364	8,805	0,893	6,469	8,473
Karar Ağacı (Decision Tree)	0,793	8,618	11,692	0,862	7,074	9,609

Random Forest, hem Li hem de GM'ler için $R^2 \approx 0,88–0,89$ ile en iyi genel performansı ve en düşük MAE/RMSE'yi sunmuştur.

Karar Ağacı, Rastgele Orman'a göre daha yüksek hatalara ve biraz daha düşük R^2'ye sahip olmasına rağmen makul derecede iyi performans göstermektedir.

Doğrusal Regresyon en zayıf performansı göstermektedir ve bu da liç sürecinde doğrusal olmayan etkilerin önemli olduğunu göstermektedir.

Bu sonuçlar, Rastgele Orman modelin, liç süreçlerindeki karmaşık, doğrusal olmayan etkileşimleri yakalamak için oldukça uygun olduğunu doğrulamaktadır.

3.3. SHAP analizi bulguları

Analizin devamında modelin nasıl çalıştığını daha iyi anlamak için SHAP grafikleri oluşturulmuştur. SHAP grafikleri, makine öğrenmesi modellerinin karar verme süreçlerini daha anlaşılır hale getirmek için kullanılan güçlü yorumlama araçlarıdır. Bu yöntem, her bir girdinin model çıktısına ne kadar katkı sağladığını matematiksel olarak hesaplayarak, modelin neden belirli bir tahminde bulunduğunu açıklar. SHAP grafikleri, her bir girdinin model tahminine olan katkısını pozitif veya negatif yönde göstererek, değişkenlerin önem sırasını ve etkisini görselleştirir. Genellikle yatay eksende SHAP değeri yer alır; bu değer büyüdükçe girdinin model tahmini üzerindeki etkisi artar. Renk skalası ise ilgili girdinin düşükten yükseğe değer aldığını gösterir. Pozitif SHAP değerleri, tahmini artırıcı; negatif SHAP değerleri ise tahmini azaltıcı etki anlamına gelir. Böylece hem hangi değişkenlerin daha

belirleyici olduğu hem de bu değişkenlerin nasıl bir etki yönüne sahip olduğu açıkça yorumlanabilir.

Li için SHAP grafiği Şekil 2-a'da verilmiştir. Bu grafiğe göre aşağıdaki yorumlar yapılabilir:

Sıcaklık: En etkili özellik. Yüksek değerler (kırmızı) Li liç oranını (pozitif SHAP değerleri) önemli ölçüde artırır.

Aynı zamanda düşük sıcaklıklar (mavi) tahmini önemli ölçüde azaltır. Bu durum sıcaklık değişiminin büyük ölçüde etkisinin olduğunu gösterir.

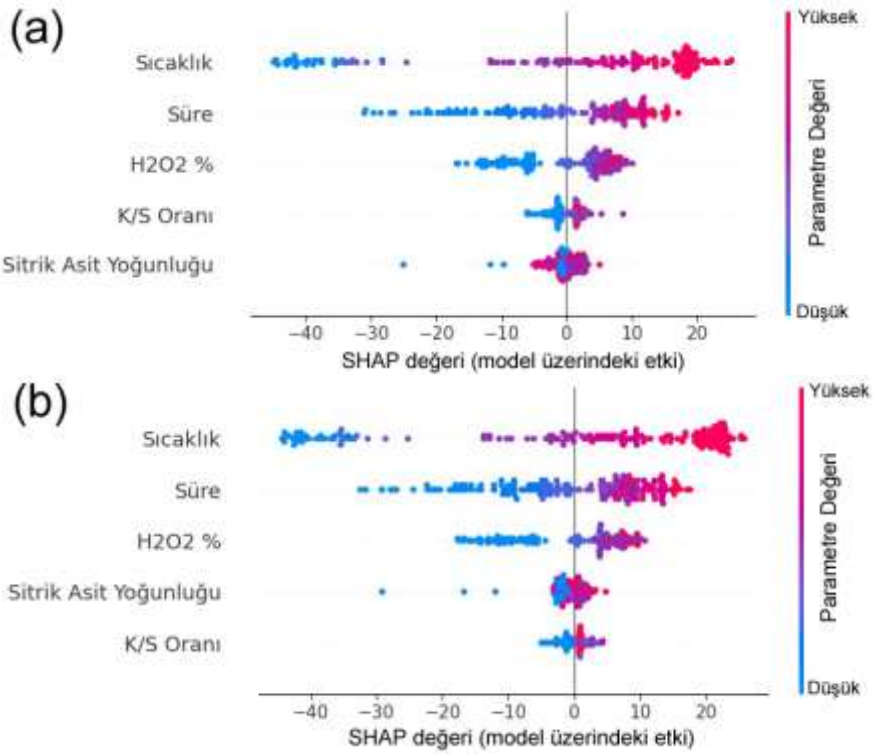
Süre: Sıcaklık kadar olmasa da güçlü bir etkiye sahiptir. Süre değişikliği tahminde büyük değişikliğe yol açıyor.

H_2O_2% : Eklenmesi çözünme üzerinde orta derecede olumlu etkisi görülmektedir.

K/S Oranı: Çok net bir ayrım yoktur. Hem yüksek hem de düşük değerler tahminleri her iki yönde de etkileyebilir. Bu durum doğrusal olmayan veya diğer parametrelerle etkileşimli bir etkiye işaret ediyor olabilir.

Sitrik Asit Yoğunluğu (Sitrik Asit Konsantrasyonu): Şaşırtıcı bir şekilde bu modelde parametreler arasında en az etkili olanıdır.

GM için SHAP grafiği Şekil 2-b'de verilmiştir. Li için yapılan yorumlar büyük ölçüde GM için de geçerlidir. Fakat sitrik asidin yoğunluğu GM'ler için Li'den biraz daha etkili olduğu görülmektedir. Ayrıca H_2O_2'ye baktığımızda yüksek olduğunda pozitif etkisi olduğu anlaşılmaktadır (kırmızı), ancak Li'ye kıyasla daha az belirgindir. Bu, GM'lerin Li'ye kıyasla H_2O_2 artışına daha az bağlı olabileceğine işaret edebilir.



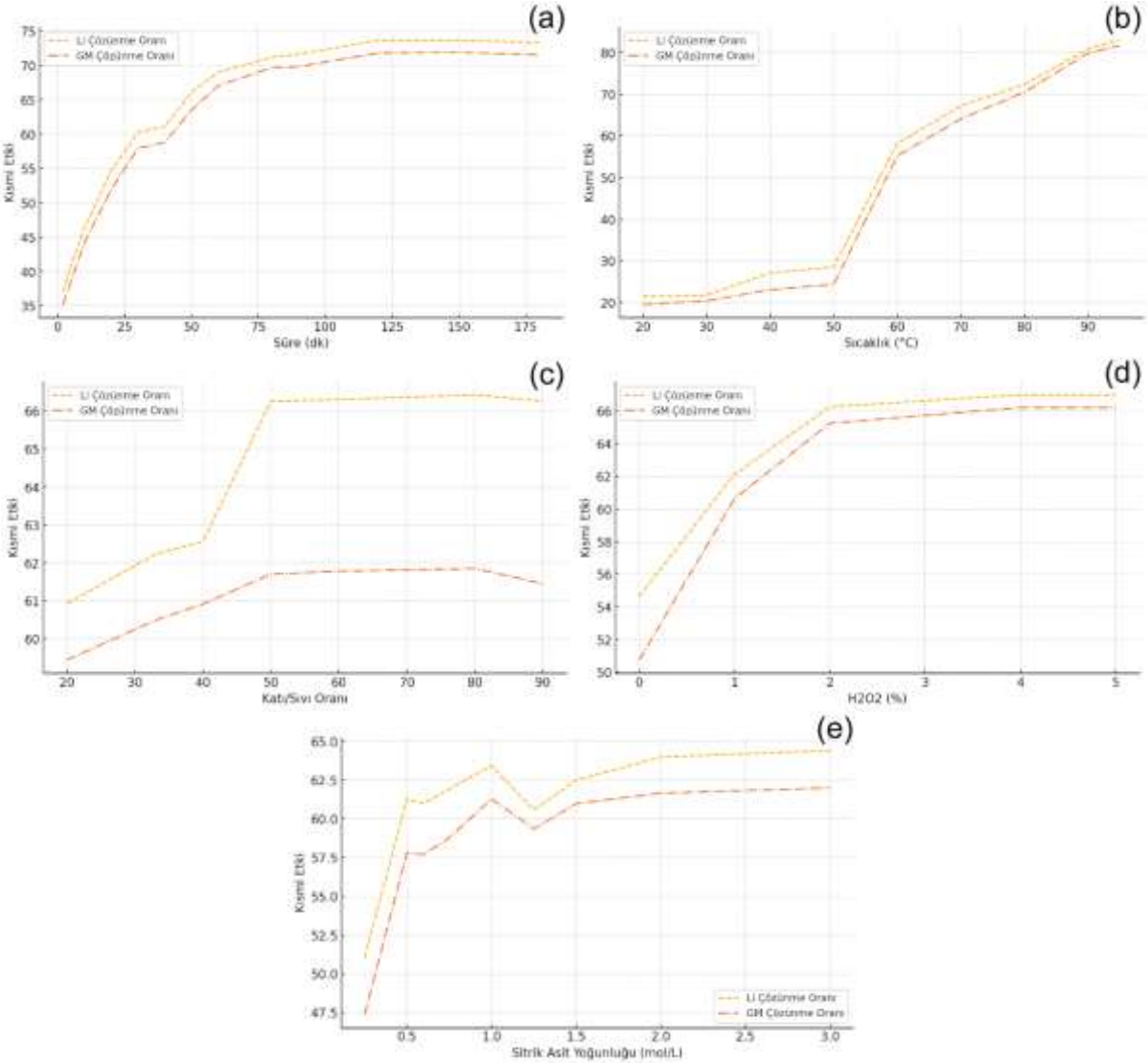
Şekil 2. Rastgele Orman modeline göre SHAP grafikleri

Literatürdeki benzer bir çalışmaya (Niu ve ark., 2023) bakıldığında her iki çalışmada da sıcaklık, süre, H_2O_2 ve asit konsantrasyonu gibi parametrelerin model üzerindeki etkisi benzer şekilde değerlendirilmiştir. Ancak pulp density (katı/sıvı oranı) bu çalışmada görece daha düşük önem derecesine sahipken, literatürde (Niu ve ark., 2023) ikinci sırada yer almıştır. Bu fark, Niu ve arkadaşlarının çalışmasında pulp density aralığının çok geniş tutulması (2–300 g/L) ve farklı asit sistemlerinin (organik ve inorganik) kullanılması ile açıklanabilir. Ayrıca, bu çalışmada yalnızca sitrik asit kullanılması, pulp density'nin çözünme verimleri üzerindeki etkisinin daha sınırlı gözlenmesine neden olmuş olabilir. Oysa literatürde farklı asit türlerinin (özellikle güçlü inorganik asitlerin ve karışım sistemlerinin) kullanılması, pulp density'nin metal çözünürlüğü üzerinde daha belirleyici bir faktör hâline gelmesine yol açmıştır. Bu durum SHAP analizinde gözlenen parametre sıralamasındaki farklılığın başlıca nedenlerinden biri olabilir.

3.4. PDP (partial dependence plot) bulguları

Analizlerin son aşamasında PDP grafikleri çizilmiştir. Bu grafikler bir veya iki bağımsız değişkenin hedef değişken üzerindeki ortalama etkisini görselleştirmek için kullanılan yorumlayıcı araçlardır. Bu grafikler, modelin diğer tüm değişkenlerini sabit tutarak yalnızca ilgili değişkenin nasıl bir etki oluşturduğunu gösterir. Yatay eksende bağımsız değişkenin değeri yer alırken, dikey eksende bu değişkenin model çıktısına olan ortalama etkisi gösterilir. Böylece, değişkenin artması ya da azalması durumunda modelin nasıl tepki verdiği analiz edilebilir. PDP grafikleri, özellikle deneysel tasarımlarda parametrelerin hedef çıktılar üzerindeki eğilimlerini anlamak ve optimize etmek açısından önemli bilgiler sunar. Farklı değişkenler için çizilen PDP grafikleri Şekil 3'te gösterilmiştir. Bu grafikler her değişkenin Li ve GM liç oranı üzerindeki etkisini anlatmaktadır. Şekil 3-a liç süresinin etkisini göstermektedir. 0–60 dakika arası her iki çözünme oranında da belirgin bir artış görülüyor. Bu, reaksiyonun başlangıç aşamasında kinetiğin hızlı olduğunu ve çözünmenin bu dönemde daha etkin gerçekleştiğini gösteriyor. 60–120 dakika arası artış devam etse de, eğim giderek azalıyor. Bu durum, çözünmenin doygunluk eğilimine girdiğini, yani sistemdeki reaktiflerin sınırlandığını düşündürüyor. 120–180 dakika arası her iki çözünme oranı da plato yapıyor. Bu, daha uzun sürelerin ilave fayda sağlamadığını, optimal sürenin yaklaşık 120 dakika civarında olduğunu gösteriyor. Li Çözünme Oranı, GM çözünme oranına kıyasla her aşamada biraz daha yüksektir. Bu, Li'nin daha kolay veya daha hızlı çözündüğünü gösteriyor olabilir.

Şekil 3-b sıcaklığın etkisini göstermektedir. 20–50 °C arası her iki çözünme oranı düşük seviyelerde ve oldukça durağan. Bu sıcaklık aralığında sistemin kinetik olarak yavaş çalıştığı anlaşılıyor. 50–60 °C arası her iki çözünme oranında çok belirgin bir sıçrama var. Bu nokta, kritik bir eşik gibi görünüyor ve aktivasyon enerjisinin aşıldığı bir aralık olabilir. 60–90+ °C arası artış devam ediyor ancak eğim daha yatık hale geliyor. Bu da çözünmenin verimli şekilde sürdüğünü, ancak sıcaklığın etkisinin artık giderek sınırlı hale geldiğini gösteriyor. Li çözünme oranı, her sıcaklık seviyesinde GM çözünme oranından biraz daha yüksek kalıyor. Özellikle 60–80 °C aralığı, hem Li hem de GM için optimum çözünme eğiliminin sağlandığı aralık gibi görünüyor. 90 °C ve üstü ise yüksek çözünürlük oranı sunmakla birlikte, enerji maliyeti açısından değerlendirilmelidir.



Şekil 3. Farkı parametreler için PDP grafiği, a) süre, b) sıcaklık, c) katı/sıvı oranı, d) H_2O_2 oranı ve d) asit yoğunluğu

Şekil 3-c liç işlemlerinde katı/sıvı oranının (g/L) hem Lityum (Li) hem de Geçiş Metallerinin (GM) çözünme oranları üzerindeki etkisini gösteriyor. 20–40 g/L arası kısmi etkide hafif ama kararlı bir artış söz konusu. Çözünme performansı bu aralıkta düzenli şekilde iyileşiyor. 40–50 g/L arası her iki eğrinin de belirgin biçimde sıçrama yaptığı bir bölge. Bu, çözünme mekanizmasının bu aralıkta daha verimli çalıştığını ve sistemde yeterli etkileşim ortamının oluştuğunu gösteriyor. 50–90 g/L arası kısmi etkiler plato yapıyor. Li çözünme oranı sabitlenmiş gibi görünürken, GM çözünme oranında 80'den sonra çok hafif bir düşüş gözleniyor. Aşırı yüksek S/L oranları, çözünme oranını sınırlayabilir. Bu, sıvı fazdaki iyon transferinin zorlaşması veya çözeltide doygunluk yaklaşmasıyla açıklanabilir. Optimum bölge 40–60 g/L arası gibi görünüyor — çözünme verimi yüksek, ancak sistem hâlâ akışkan kalabiliyor. Li çözünme oranı tüm değerlerde GM'ye göre daha yüksek ve daha istikrarlı. Ancak GM için eğri daha duyarlı, S/L oranı arttıkça çözünme daha erken sabitleniyor, yani katı faz fazlalığı GM çözünmesini biraz daha olumsuz etkileyebilir.

Şekil 3-d liç sisteminde oksitleyici ajan olarak kullanılan H_2O_2'nin (yüzde konsantrasyon olarak) hem Lityum (Li) hem de Geçiş Metallerinin (GM) çözünme oranlarına

olan etkisini gösteriyor. 0–2% H_2O_2 arası hem Li hem de GM çözünme oranlarında belirgin bir artış görülüyor. Bu, H_2O_2'nin etkili bir oksitleyici olduğunu ve özellikle bu aralıkta reaksiyon kinetiğini ciddi oranda hızlandırdığını gösteriyor. 2–5% H_2O_2 arası artış devam ediyor ancak çok daha düşük eğimle. Eğriler plato eğiliminde; sistem artık H_2O_2'den sınırlı fayda sağlıyor olabilir. Özellikle 2% seviyesinden sonra, çözünme oranları doygunluğa ulaşıyor. H_2O_2, özellikle TM'lerin (örneğin $Co^{3+} \rightarrow Co^{2+}$ gibi) redoks dönüşümleri için kritik rol oynar. Oksijen radikalleriyle daha fazla metal iyonunu çözeltide tutabilir. Ancak aşırı H_2O_2 kullanımı, bazı sistemlerde çözeltinin stabilitesini bozabilir (özellikle asidik ortamda bozunma ile O_2 çıkışı), bu nedenle ekonomik ve teknik açıdan optimum değer 2–3% gibi görünüyor. H_2O_2 artışı her iki çözünme oranını da artırsa da, GM çözünme oranı H_2O_2'ye daha hassas görünüyor (daha dik eğim). Li çözünürlüğü ise zaten yüksek olduğundan, H_2O_2 ile daha sınırlı bir artış göstermiş olabilir. Şekil 3-d liç çözeltisinde kullanılan sitrik asidin molar konsantrasyonunun etkisini göstermekte. 0.1–0.5 mol/L aralığı her iki çözünme oranında da çok belirgin bir artış görülüyor. Bu, sistemin düşük asit konsantrasyonlarında çözünmeye çok duyarlı olduğunu ve iyonlaşmanın hızlı arttığını gösteriyor. Her ne kadar 1.0–1.5 mol/L aralığında küçük bir dalgalanma gözlense de, bu sapma büyük olasılıkla deneysel gürültü veya model kaynaklı olabilir. Bu nedenle genel eğilim dikkate alındığında, artan sitrik asit konsantrasyonu ile hem Li hem de GM çözünme oranlarının istikrarlı biçimde yükseldiği söylenebilir. 2 mol/L'den sonra neredeyse plato çiziyor. Bu aralıkta çözünme oranları artık doygunluğa ulaşmakta. Sitrik asit, hem pH düşürücü hem de kompleks oluşturucu (şelatlayıcı) ajan olarak çalışır. Bu nedenle özellikle GM iyonlarının çözünmesinde çok etkili. Ancak çok yüksek konsantrasyonlarda, kompleks dengesi kararsızlık yaratabilir ya da çözelti viskozitesi artarak difüzyonu kısıtlayabilir. Li çözünme oranı daha yüksek, ancak GM çözünme oranı daha kararlı bir artış gösteriyor. Li çözünürlüğü daha erken doygunluğa ulaşsa da, kompleksleme davranışları farklı olduğu için GM eğrisi daha düzenli seyrediyor.

Niu ve arkadaşlarının (Niu ve ark., 2023) çalışmasına elde edilen sonuçlar genel eğilimler bakımından tutarlı olmakla birlikte, bazı parametrelerde dikkat çekici farklar gözlemlenmiştir. Örneğin, her iki çalışmada da sıcaklık artışı Li çözünürlüğünü anlamlı şekilde artırmakta, ancak Niu ve arkadaşlarının çalışmasında bu artış daha yüksek sıcaklıklarda (90 °C civarı) doygunluğa ulaşırken, bizim çalışmamızda optimum aralık 60–80 °C olarak tespit edilmiştir. Benzer şekilde, süre parametresi her iki çalışmada da 90–120 dakika aralığında plato eğilimi göstermekte olup, çözünme tepkimesinin bu aralıkta tamamlandığı görülmektedir. Katı/sıvı oranı açısından ise belirgin bir fark dikkat çekmektedir: Bizim çalışmamızda 40–60 g/L aralığı optimum değerler sunarken, Niu ve arkadaşlarının çalışmasında K/S oranı çok daha geniş aralıkta değerlendirilmiş ve maksimum çözünme ~100 g/L dolaylarında gerçekleşmiştir. Bu durum, bizim çalışmamızda kullanılan tek asit tipi (sitrik asit) ve veri aralığının daha dar olmasıyla açıklanabilir. H_2O_2 oranı için her iki çalışmada da %2–3 aralığında optimum etki gözlenmiş, ancak Niu ve arkadaşlarının çalışmasında bu etki daha erken plato eğilimi göstermiştir. Son olarak, asit konsantrasyonu arttıkça Li çözünürlüğü her iki çalışmada da artmakta, ancak 1.5–2.0 mol/L sonrası doyum noktasına ulaşılmaktadır. Bu bulgular, her iki modelin genel eğilimleri benzer şekilde yakaladığını, ancak deneysel parametre aralıkları ve kullanılan asit türü gibi etkenlerin çözünme davranışları üzerinde belirleyici olduğunu ortaya koymaktadır.

4. Sonuç

Bu çalışmada, NMC tipi lityum-iyon pillerin hidrometalurjik geri dönüşüm süreçlerinde kullanılan temel liç parametrelerinin çözünme verimi üzerindeki etkisi, makine öğrenmesi teknikleri kullanılarak incelenmiştir. SHAP ve PDP analizleriyle desteklenen modelleme sonuçları, deneysel bulguların sayısal olarak yorumlanmasına ve süreç optimizasyonuna katkı sağlamaktadır.

Modelleme sürecinde Random Forest algoritması, doğrusal ve karar ağacı modellerine kıyasla daha yüksek doğruluk ve daha düşük hata değerleri ile öne çıkmıştır. Bu durum, liç süreçlerinde değişkenler arasındaki etkileşimlerin karmaşık ve doğrusal olmayan yapıda olduğunu ortaya koymaktadır. SHAP analizleri, sıcaklık ve sürenin Li çözünme oranı üzerinde en belirleyici faktörler olduğunu göstermiştir. PDP grafiklerine göre bu parametrelerin artışı çözünme oranını anlamlı ölçüde artırmakta; ancak 120 dakika süre ve 60–80 °C sıcaklık aralığında doygunluğa ulaşılmaktadır. H_2O_2 oranı ve sitrik asit konsantrasyonu ise özellikle geçiş metallerinin çözünürlüğünde etkili olmuş; 2–3% H_2O_2 ve 1–2 mol/L sitrik asit aralıkları optimum değerler olarak öne çıkmıştır. Katı/sıvı oranı için ise 40–60 g/L aralığı hem Li hem de GM çözünmeleri açısından dengeli ve verimli sonuçlar sunmuştur. PDP grafiklerinde bazı aralıklarda görülen küçük dalgalanmaların, model gürültüsü ya da veri dengesizliğinden kaynaklanabileceği ve genel eğilime odaklanmanın daha doğru olacağı değerlendirilmiştir. Bu analizler, parametrelerin bağımsız etkilerini görselleştirerek deney tasarım süreçlerine önemli katkılar sağlayacak niteliktedir.

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Microstructural and Dielectric Characterization of MgO-added Al_2O_3-based Ceramics in the Terahertz Range

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Abstract
This study investigates the effect of MgO addition on the microstructural and dielectric properties of Al2O3 ceramics. The dielectric properties of Al2O3-based ceramics with MgO addition were investigated in the terahertz (THz) range. The fabricated ceramic composites are characterized utilizing THz time-domain spectroscopy (THz-TDS). The relative density reached 99.5% with the addition of MgO, while the particle size decreased significantly. Although microstructural analysis indicated a more homogeneous distribution, complete effectiveness could not be achieved. THz-TDS measurements revealed that MgO-added samples exhibited a higher dielectric constant, lower absorption coefficient, and reduced loss tangent. These findings confirm that, although MgO cannot entirely suppress grain growth, it effectively reduces dielectric losses and enhances the suitability of Al2O3-based ceramics for terahertz applications.

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1. Introduction

Terahertz (THz) radiation, typically defined in the frequency range of 0.1–10 THz, has attracted increasing attention in recent years due to its unique ability to penetrate many non-conductive materials while being non-ionizing and safe for biological tissues (Tonouchi, 2007). Owing to these properties, THz technology has found promising applications in fields such as biomedical imaging, security screening, non-destructive testing, wireless communications, and materials characterization. However, despite these broad prospects, the practical implementation of THz systems is often limited by the availability of suitable materials and components that can operate efficiently in this spectral region. Ceramic materials stand out as strong candidates for THz applications because of their high thermal stability, mechanical properties, and tunable dielectric properties. In particular, alumina (Al_2O_3)-based ceramics have been extensively investigated as substrates, dielectric components, and protective coatings for THz devices (Naftaly et al., 2009). Their relatively low dielectric loss, chemical stability, and compatibility with various processing methods, including additive manufacturing, make them highly attractive for the development of advanced THz components. Moreover, by tailoring their microstructure, porosity, or by introducing specific additives, the dielectric response of ceramics in the THz band can be significantly modified, opening pathways for both low-loss transmission components and high-resolution imaging systems.

Hakobyan et al. (2022) investigated the dielectric properties of Al_2O_3 ceramics with different porosity ratios (0, 5, 10, 15, and 20 vol.%) in the THz frequency range (0.4–2 THz). The study revealed a linear relationship between the porosity ratio of the samples and both the dielectric constant and the dielectric loss tangent in the THz frequency range. (Hakobyan et al., 2022). In another study, the densification, microstructure, and dielectric properties in the 0.3–1.5 THz frequency range of Al_2O_3-based ceramics containing samarium oxide (Sm_2O_3) and ZrO_2 additives separately and together were investigated. It was found that the addition of ZrO_2 increased the refractive index, whereas the addition of Sm_2O_3 reduced the losses. Therefore, Al_2O_3-based ceramics with ZrO_2 additives were emphasized as suitable for applications requiring higher confinement and enhanced resolution, whereas Sm_2O_3-added Al_2O_3 ceramics were indicated for applications where low losses are essential (Purlu et al., 2025). Palka et al. utilized THz radiation for the non-destructive evaluation of assess damage in Al_2O_3 ceramic ballistic armor samples. The THz-TDS technique was employed to determine the refractive indices of the materials, which were then used in simulations based on the transfer matrix method. Using the transfer matrix method, the THz signals reflected from the sample were accurately simulated, the thicknesses of the sample layers were determined, and hidden defects were successfully identified. Additionally, the THz-TDS has been reported as an effective method for the non-destructive 3D imaging of Al_2O_3-based ballistic armor (Pałka et al., 2024). The dielectric behavior of Al_2O_3 ceramics produced through a stereolithography-based additive manufacturing method was investigated by Ornik et al. The study determined the refractive index and absorption coefficient of Al_2O_3 ceramics in a wide frequency range (0.3–2.5 THz). It was reported that samples produced via additive manufacturing exhibit a high refractive index ($n>3$) and a low absorption coefficient (<2 cm^{-1} at 1 THz), highlighting the broad opportunities offered by additive manufacturing for implementing complex structures and compact devices in the THz frequency range (Ornik et al., 2021).

In this study, the dielectric properties of MgO-added Al_2O_3-based ceramics prepared by dry pressing were systematically investigated in the THz frequency range. This work uniquely focuses on the THz dielectric loss behavior of MgO-modified Al_2O_3, a topic that has not been systematically examined in the existing literature. In addition, the densification

and microstructural characteristics of the samples were analyzed to explore the correlation between their microstructure and dielectric response. The results are presented in a comparative manner between pure Al_2O_3 and MgO-added compositions.

2. Material and Method

2.1. Sample preparation and microstructural characterization

In this study, the raw materials were α-Al_2O_3 powder (purity 99.95%, 0.25-0.45 average grain size, Alfa Aesar), magnesium nitrate ($Mg(NO_3)_2.6H_2O$, Sigma Aldrich) as the MgO source, polyacrylic acid (Darvan 821A, MSE Tech Co. Ltd., Turkey) as the dispersant, polyvinyl alcohol as the binder (PVA, binder, Sigma Aldrich), and glycerol as the plasticizer (Sigma Aldrich). For the fabrication of pure Al_2O_3 samples, α-Al_2O_3 powder and 0.5 wt% dispersant were ball-milled in distilled water for 24 hours. A binder solution containing 2 wt% polymer was added to the ball-milled powder. Subsequently, the prepared powder mixture was dried, ground in an agate mortar, and granulated by sieving through a 90 μm mesh. For the samples containing MgO, the ball-milled and dried powder mixture with magnesium nitrate was calcined at 800 °C for 2 h before the binder solution was added. Through this calcination process, MgO was obtained from the $Mg(NO_3)_2.6H_2O$ source. To provide a homogeneous distribution of MgO in the microstructure, MgO was obtained through calcination from the $Mg(NO_3)_2.6H_2O$ source instead of using MgO powder directly. After the calcination process, the binder solution was added to the powder mixture, followed by drying, grinding, and sieving. The granulated powders were initially shaped using a uniaxial press at 40 MPa and subsequently subjected to cold isostatic pressing at 200 MPa. The production parameters were determined based on the results of previous studies (Taşdemir et al., 2023; Kafkaslıoğlu Yıldız et al., 2024; Usta et al., 2024).

The pressed samples were exposed to a binder burn-out process at 600°C for 2 hours, then pressureless sintered at 1600°C for 2 hours in air atmosphere. A lapping process was applied to grind and parallelize the surfaces of the sintered samples. The density of the fabricated samples was determined via Archimedes' method. The relative density is calculated as the ratio of the experimental density to the theoretical density of the ceramic sample. The theoretical densities of the MgO-added samples were calculated according to the mixing rule. For microstructural analysis, the samples were thermally etched for 90 min at 1500°C. The microstructural analysis of the thermally etched samples was carried out using scanning electron microscopy (SEM). The grain size measurements were also performed on SEM images using the linear intercept method (Usta et al., 2024).

2.2. Dielectric properties characterization

The dielectric properties of the ceramic samples were investigated using a terahertz time-domain spectroscopy (THz-TDS) system operating in transmission mode. In this technique, ultrafast femtosecond laser pulses generate broadband THz radiation, which is transmitted through the sample, and the transmitted electric field is directly recorded in the time domain. This allows simultaneous access to both amplitude and phase information of the THz wave, enabling the extraction of complex dielectric parameters without relying on Kramers–Kronig relations. In the present study, measurements were performed using a Toptica Photonics TeraFlash Pro system, which provides a dynamic range of approximately 95 dB and a spectral bandwidth extending up to 6 THz. The setup includes a high-precision mechanical delay stage capable of scanning a 50 ps time window, recording up to 60 temporal waveforms per second. Prior to each measurement, a reference spectrum was recorded. The collected time-domain signals were converted into frequency-domain spectra via fast Fourier transform (FFT). From these spectra, the complex refractive index $\tilde{n}$

$(\omega)=n(\omega)+i\kappa(\omega)$ was determined, where $n(\omega)$ is the real refractive index and $\kappa(\omega)$ is the extinction coefficient. The absorption coefficient was calculated from (Purlu et al., 2025):

$$\alpha(\omega)=2\omega\kappa(\omega)/c \quad \textbf{1)}$$

where c is the speed of light. The real part of permittivity was obtained from $\varepsilon'(\omega)\approx n2(\omega)$, while the imaginary part $\varepsilon''(\omega)$ was derived from the extinction coefficient. The dielectric loss tangent was then calculated as (Purlu et al., 2025):

$$\tan\delta=\varepsilon''/\varepsilon' \quad \textbf{2)}$$

Sample thicknesses were precisely measured with a micrometer (accuracy ±5 μm) and incorporated into the calculations. Data analysis was carried out using a custom MATLAB routine to extract frequency-dependent refractive index, permittivity, absorption coefficient, and loss tangent in the 0.3–1 THz range.

3. Results and Discussion

3.1. Density measurement and microstructural analysis

Table 1 presents the relative density and grain size values of the pure Al_2O_3 and Al_2O_3-MgO samples (abbreviated as AlMgO). Based on the results, the relative density increased from 98.9% to 99.5% after the addition of MgO. This indicates that the MgO additive acts as a sintering aid and enhances densification. A similar effect was observed in the grain size, which was found to decrease with the addition of MgO. The high sintering temperature (1600°C) resulted in grain growth in the pure Al_2O_3 sample. It can be seen in the SEM images in Fig. 1 that the grain size distributions of the pure Al_2O_3 samples are not homogeneous, with large grains forming alongside very fine grains. It was observed that, with the addition of MgO, the grain size decreased to 4.1 μm and the grain size distribution became more uniform compared to that of pure Al_2O_3. However, despite the decrease in grain size in AlMgO samples, the presence of large grains in the microstructure indicates that MgO was not entirely effective with the possibility of not being sufficiently homogeneously distributed. The literature reports that the addition of MgO inhibits grain growth, resulting in a finer, more homogeneous, and denser microstructure. Consistent with these literature findings, the present study observed a reduction in grain size and an increase in densification with the addition of MgO (Rittidech et al., 2006; Yang et al., 2024).

Table 1. Relative density and grain size values of the samples

Composition	Relative Density (%)	Grain size (μm)
Pure Al_2O_3	98.9	8.0
AlMgO	99.5	4.1

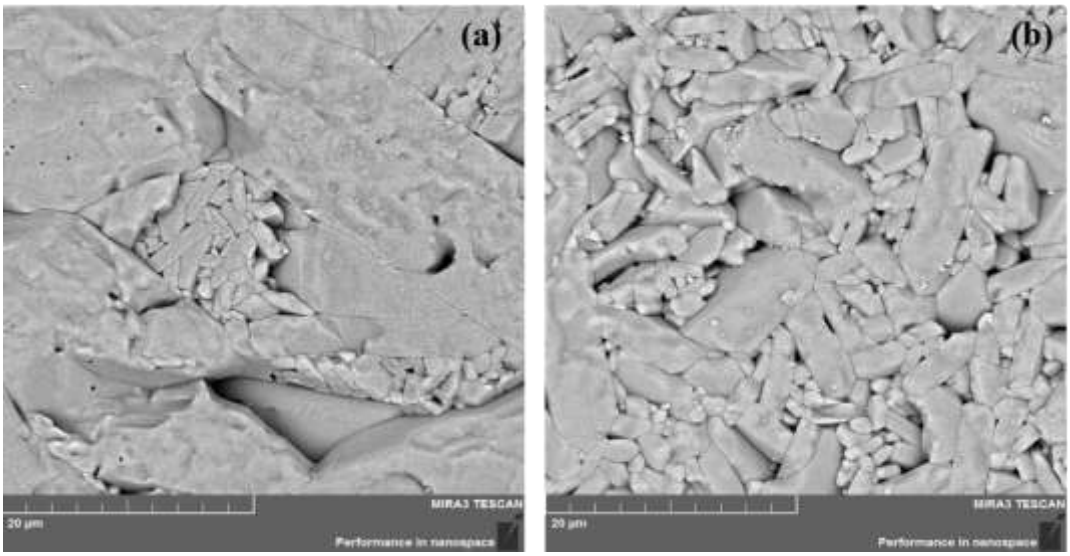

Figure 1. SEM images of the pure a) Al_2O_3 and b) AlMgO samples sintered at 1600°C for 2 h

3.2. Dielectric properties characterization

The THz-TDS measurements provided a comprehensive dataset on the dielectric response of the prepared ceramic samples, allowing the frequency-dependent refractive index, absorption coefficient, and dielectric function to be extracted. By comparing the spectral features of Al_2O_3 and AlMgO ceramics, clear trends associated with compositional modifications and microstructural effects could be observed (Gao et al., 2025). These results form the basis for the following discussion, where the impact of additive, porosity, and additive engineering on the THz optical properties of ceramics is analyzed in detail, with particular attention to their potential role in practical THz device applications.

The refractive index spectra of Al_2O_3 and AlMgO ceramics in the 0.3–1.0 THz frequency range are shown in Fig. 2. Both materials exhibited relatively stable refractive indices with only a slight frequency dispersion. Pure Al_2O_3 maintained values around $n \approx 3.05$, which is consistent with previously reported values for dense alumina ceramics (Ma et al., 2019). In contrast, the AlMgO ceramic displayed slightly higher refractive index values across the entire frequency range, starting from ~3.3 at 0.3 THz and gradually decreasing toward ~3.1 at 1.0 THz. This enhancement suggests that Mg incorporation into the alumina lattice modifies the polarization response of the material, possibly by influencing grain boundary phases and improving densification. The weak downward trend with frequency, observed in both samples, reflects normal dielectric dispersion, where the refractive index approaches a constant value at higher THz frequencies. The higher refractive index of AlMgO compared to pure Al_2O_3 indicates an increase in effective permittivity (since $\varepsilon' \approx n^2$), suggesting that Mg substitution enhances the polarizability of the ceramic matrix. This behavior highlights AlMgO as a promising candidate for THz applications requiring materials with slightly higher dielectric constants and stable refractive index behavior.

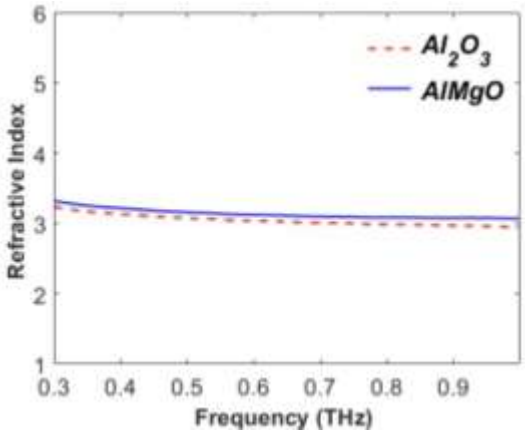

Figure 2. Refractive index of the ceramic samples in the THz range.

The absorption coefficient spectra of Al_2O_3 and AlMgO ceramics in the 0.3–1.0 THz range are presented in Fig. 3. Both materials showed an increasing absorption with frequency, consistent with typical phonon-related loss mechanisms in the THz region. Pure Al_2O_3 exhibited significantly higher absorption values compared to AlMgO, exceeding 20 cm^{-1} at 1.0 THz. In contrast, AlMgO ceramics displayed lower absorption coefficients across the entire spectrum, remaining below 15 cm^{-1} at the upper frequency limit. At low frequencies (<0.5 THz), the difference between the two materials was minimal; however, as the frequency increased, the separation became more pronounced. This indicates that Mg incorporation into the alumina lattice effectively suppresses high-frequency scattering and reduces vibrational losses (Gao et al., 2025). This reduction in absorption in AlMgO can be directly linked to the microstructural modifications induced by MgO. As reported in previous studies, Mg addition inhibits abnormal grain growth and promotes a finer and more densely packed microstructure. (Rittidech et al., 2006; Yang et al., 2024). In our samples as well, grain refinement and improved densification were observed. Such microstructural refinement reduces phonon–boundary scattering and suppresses defect-mediated vibrational damping, both of which contribute to THz absorption. Consequently, fewer high-frequency scattering pathways are available in AlMgO, leading to a lower overall absorption coefficient. Therefore, the observed trends confirm that Mg incorporation effectively mitigates phonon-related loss processes, making AlMgO a lower-loss dielectric material than pure Al_2O_3, particularly for applications operating above 0.7 THz.

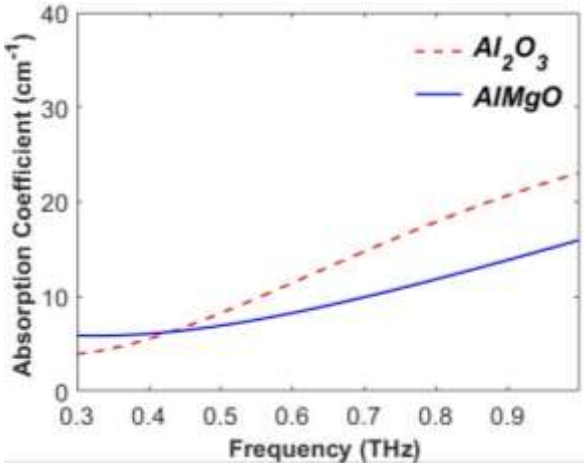

Figure 3. Absorption coefficient of the ceramic samples in the THz range.

The dielectric loss tangent spectra of Al_2O_3 and AlMgO ceramics are shown in Fig. 4. Pure Al_2O_3 exhibited tan δ values in the range of 0.05–0.1, with a gradual increase as the frequency approached 1.0 THz. This frequency-dependent rise in dielectric losses can be attributed to enhanced phonon–polariton interactions and extrinsic scattering from grain boundaries and residual porosity. By contrast, the AlMgO ceramic consistently demonstrated lower loss tangent values across the entire frequency range, remaining below 0.05 even at 1.0 THz. At low frequencies (<0.5 THz), AlMgO maintained tan δ values around 0.02–0.03, almost half of that measured for pure Al_2O_3. This reduction indicates that Mg incorporation effectively suppresses dielectric dissipation mechanisms (Wang et al., 2013). The reduction in dielectric loss observed in AlMgO can be directly linked to the microstructural improvements induced by MgO addition. As shown in previous studies, Mg suppresses abnormal grain growth and promotes a finer, more homogeneous, and denser microstructure. In our samples as well, a noticeable decrease in grain size and an increase in densification were observed. Such microstructural refinement reduces the density of scattering centers, enhances grain-boundary continuity, and limits defect-mediated polarization processes. These improvements effectively suppress phonon–boundary scattering and defect-related relaxation mechanisms both of which play major roles in dielectric dissipation in the THz regime. Therefore, the lower tan δ values in AlMgO confirm that Mg incorporation mitigates phonon–polariton damping and diminishes defect-assisted energy loss pathways. Overall, these results demonstrate that Mg-modified alumina ceramics provide a more favorable low-loss dielectric response in the THz region, making them better suited for THz applications where dielectric transparency and minimal energy dissipation are critical.

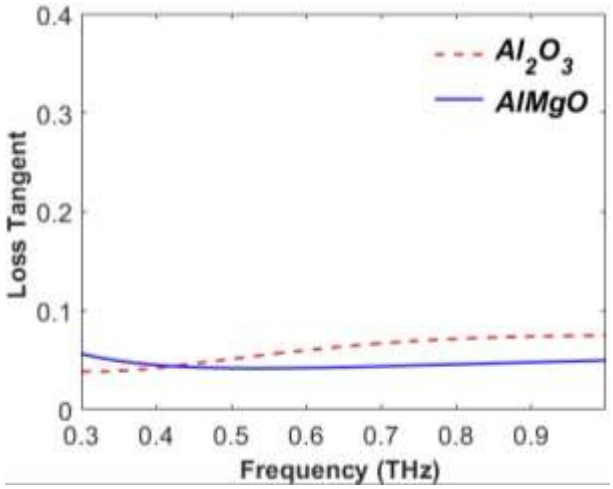

Figure 4. Loss tangent (tan δ) of the ceramic samples in the THz range.

The real part of the dielectric permittivity (ε′) of Al_2O_3 and AlMgO ceramics is illustrated in Fig. 5. Pure Al_2O_3 exhibited permittivity values around 9–9.5 in the measured range, which aligns with previously reported values for dense alumina ceramics in the THz regime (Ma et al., 2019). A mild frequency-dependent decrease was observed, with ε′ gradually decreasing from ~9.5 at 0.3 THz to ~8.7 at 1.0 THz. In contrast, AlMgO ceramics consistently displayed higher permittivity values, starting from ~11 at 0.3 THz and converging to ~9.8 at 1.0 THz. This enhancement in permittivity directly correlates with the observed increase in refractive index, as $\varepsilon' \approx n^2$, and suggests that Mg incorporation improves the polarization capacity of the ceramic. The elevated ε′ values may be attributed to enhanced densification and reduced porosity in the AlMgO structure, as well as the

possible contribution of Mg–O bonds to lattice polarizability. The frequency dispersion in both samples reflects typical dielectric behavior, where permittivity decreases with frequency due to the reduced contribution of dipolar polarization at higher THz frequencies. Nevertheless, the higher ε′ values of AlMgO across the entire spectrum indicate that Mg modification of alumina enables tuning of the dielectric constant while maintaining relatively low losses, as confirmed by the corresponding loss tangent spectra.

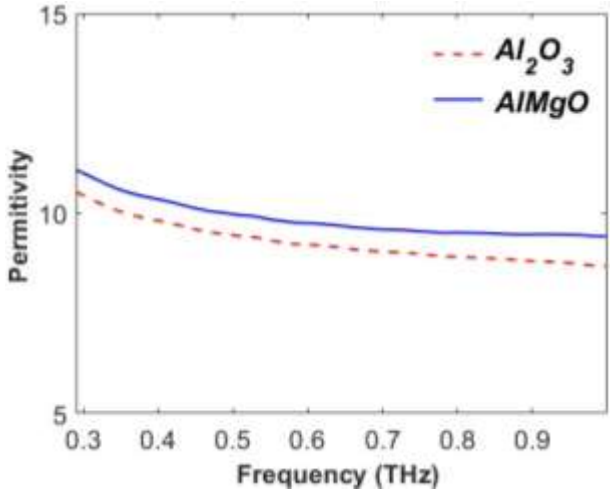

Figure 5. Dielectric permittivity (ε′) of the ceramic samples in the THz range.

Overall, the comparative THz characterization of Al_2O_3 and AlMgO ceramics demonstrates that Mg incorporation substantially modifies the dielectric response of alumina in the 0.3–1.0 THz range. AlMgO exhibited slightly higher refractive index and permittivity values compared to pure alumina, indicating enhanced polarization capability. More importantly, the absorption coefficient and dielectric loss tangent of AlMgO were consistently lower, particularly at higher frequencies, suggesting reduced phonon-related dissipation and minimized scattering from microstructural defects. These improvements are attributed to the stabilizing role of Mg in the alumina lattice, which enhances densification and suppresses extrinsic loss pathways. Consequently, AlMgO ceramics combine moderately higher permittivity with significantly reduced absorption and loss, making them promising candidates for terahertz components such as substrates, lenses, and waveguides where low-loss and stable dielectric performance are essential (Meeporn et al., 2023).

4. Conclusion

In the presented work, the densification, microstructural characteristics, and dielectric properties in the THz band of the pure Al_2O_3 and MgO-added Al_2O_3 ceramics were investigated. The relative density of samples prepared by dry pressing increased to 99.5% and the particle size decreased to 4.1 μm after the addition of MgO. Compared to the pure Al_2O_3, the grain size was found to be reduced by 48.7%. Microstructural images revealed that the addition of MgO resulted more homogeneous grain size and morphology compared to the pure Al_2O_3. However, due to the possibility of insufficiently homogeneous distribution, large grains were still present in the microstructure, and therefore MgO could not be entirely effective. The THz-TDS results further demonstrated the influence of MgO addition on the dielectric response. The refractive index of AlMgO ceramics remained slightly higher than that of pure Al_2O_3 across the measured frequency range, indicating enhanced permittivity values. More importantly, the absorption coefficient of the MgO-added samples was significantly lower, particularly at higher frequencies, leading to a

substantial reduction in dielectric losses. This trend was also confirmed by the dielectric loss tangent, which showed consistently lower values for AlMgO ceramics compared to pure Al_2O_3, highlighting their superior low-loss performance. Furthermore, the real part of the permittivity was found to be higher and more stable in the MgO-added samples, suggesting improved dielectric uniformity. These results confirm that while MgO addition alone cannot completely suppress grain coarsening, it effectively tailors the dielectric properties, reducing losses and enhancing the suitability of Al_2O_3-based ceramics for terahertz applications.

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STEAM Education and Technological Innovation: New Models of Creative Learning

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Abstract
STEAM education (Science, Technology, Engineering, Arts, Mathematics) is an innovative educational framework, which incorporates an interdisciplinary approach and creativity as central elements of the learning process. The purpose of this article is to explore the relationship between STEAM education and technological innovation, as well as to present new models of creative learning, emerging from the combination of these two fields. It examines how it contributes to the development and cultivation of modern skills, while at the same time highlighting the importance of technological innovation in shaping a modern, inclusive and innovative learning environment. In the age of technology, STEAM education, integrating digital applications, artificial intelligence, robotics, augmented and virtual reality, is particularly important for the preparation of young people and employees for the modern challenges of the ever-changing global environment.

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Creative Learning

1. Introduction

The rapid technological development that has led to the digital transformation of the economy, society, but also of many other sectors, has accelerated changes in education, schools and in general in the way the learning process is approached (Bogdandy et al., 2020; Oliveira et al., 2022). Modern educational environments based on cutting-edge technologies, such as Artificial Intelligence, Virtual, Augmented and Mixed Reality, proved to be particularly effective, due to the utilization of teaching innovations, which offered children exciting experiences and challenges, with simulations of real conditions for experiential learning (Ahmed and Sutton, 2017).

In recent years, all countries have set the integration of Information and Communication Technologies (ICT) in educational practice as the first priority of their educational policy. On the other hand, the human resources of education, due to lack of familiarity (Hussin, 2018), but also the ability to design the lesson, based on ICT (McDonald, 2017; Rich et al., 2021), are particularly reluctant to integrate new technologies and consequently didactic innovations into their teaching. For this reason, it is necessary to use ICT and the STEAM method in teacher training, enriching their digital skills, through online programs and online courses, adapted to their needs (Vander ark et al., 2020), but also allowing teachers to be fully informed about both their subject and technological developments (Darling-Hammond et al., 2020).

1.1. STEAM training

STEAM education, based on interdisciplinary learning, enhances creative thinking, cultivates social skills, and contributes to the all-round cognitive, emotional, and psychomotor development of students (Wu et al., 2022). After all, art has been added to the older method (STEM) in recent years, in order to cultivate children's creativity and aesthetic perception (Spyropoulou and Kameas, 2024). The addition of Art was considered necessary to enhance critical, creative thinking, holistic learning, and students' ability to tackle complex problems more effectively (Bertrand and Namukasa, 2020; Huser and Wadsworth, 2020). The positive effects of the method are multiplied when interdisciplinarity is enhanced by digital applications, such as artificial intelligence, robotics, smart devices, coding, etc. (Marín et al., 2021), making it a powerful method for the inclusion of students with learning difficulties (Tomar and Garg, 2021; Holmes and Tuomi, 2022).

The flexibility and adaptability of the STEAM framework in the utilization of new ideas and technologies, enables it to evolve and offer innovative teaching practices (Soroko, 2021a; Soroko, 2021b). Through interdisciplinary learning and the activation of modern teaching methods, a new educational framework is formed, which is more adapted to the labor market, emphasizing on emerging scientific institutions, such as natural sciences, technology, engineering and mathematics, had already been felt with the spread of industry in all productive sectors.

The integration of STEAM education in teaching is one of the most important factors of sustainable development, where along with technical, digital skills, social skills are also cultivated, such as communication, collaboration, critical thinking, problem solving, etc. (Xanthoudaki, 2017). This is achieved because both brain areas, convergent and divergent thinking, are utilized during teaching. After all, activities that require cooperation and teamwork, the high involvement of the student to solve a problem, the fact that knowledge is linked to everyday life, serve this purpose.

In recent years, the STEAM method has been influenced by contemporary emerging theories and practices that emphasize the role of technology in interdisciplinary learning. The integration of Data Science, the Internet of Things, Virtual, Augmented and Mixed Reality

(AR, VBR, MR), as well as other emerging technologies, has provided new opportunities for experiential learning and reflects a more general shift towards interdisciplinary approaches that further blur the boundaries between different disciplines (Chen et al., 2020; Liston et al., 2022).

1.2 The role of artificial ıntelligence (AI)

The question of whether a machine can "think" was first posed in 1950 by Turing (Tartuk, 2023). Artificial intelligence, linked to computer science, can generate symbolic inferences or promote logical behaviors (Demir and Güraksın, 2022), while in education it can be used in the fields of science, technology, engineering, and perform cognitive tasks related to the human mind, such as learning and problem-solving (Tartuk, 2023).

In today's conditions, the research interest in the smooth relationship between Computational Thinking (humans) and machine learning (computers) remains alive (Dohn, Kafai et al., 2022). After all, there is an inextricable relationship between Computational Thinking and Artificial Intelligence. Machine learning (ML), for example, relies on algorithms relevant to decision-making as they arise through data analysis or the algorithm-based type of Natural Language Processing (NLP) that understands natural language and promotes human-machine communication (Bellini et al., 2022).

The applications of AI contribute substantially to the upgrading of the quality of education, through the promotion of technological and teaching innovations. For example, ChatGPT enables dialogue, provides answers to questions, can process natural language, translate, provide text summaries, and generate text of various formats and styles (Malekos, 2023). Chatbots respond in real-time, solve queries, guide and support. Gradescope, a digital assessment platform, which has various grading tools that teachers can use, to grade faster, to give clear feedback to students, and to be informed about the degree of understanding of the concepts to be taught (Holmes and Tuomi, 2022; Hardman, 2023).

Also, the creation of simulations through AI applications provide an adaptive and active learning experience. In this way, students are given the opportunity to set hypotheses, experience their results and find out if the intended goals have been achieved. The simulation utilizes virtual, augmented and mixed reality or is a computer-based simulation or belongs to the serious games (Chih-Pu and Fengfeng, 2022).

Enhancing STEAM education with the help of artificial intelligence is one of the realities of our time. For example, the use of the Digital Personal Image Classifier (PIC) tool for image recognition, modeling, and application helps students learn basic engineering concepts. Thus, with the help of AI, children recognize images, with the experiment they understand Physics, create programs, apply electromechanical reactions and follow specific steps in solving problems (Hsu et al., 2021). According to the above, Artificial Intelligence includes and utilizes a wide range of technologies and approaches, such as machine learning, natural language processing (NLP), the use of computers and robotics (Dwivedi et al., 2021).

1.3. Robotics

Robotics combines AI with mechanical engineering to create machines that can perform human tasks and in doing so has the potential to change many areas of human activity, such as industry, agriculture, healthcare, and even the possibility of space exploration (Ertel, 2017). For example, large and small robotic arms enhance industrial production, while robots are leveraged from housekeeping services, to educational robots used to teach students STEM (Science, Technology, Engineering, and Mathematics) concepts, help them develop problem-solving skills, and encourage them to explore the world around them. Finally, robots can be

used as virtual assistants in the classroom, providing support to children and teachers (Shao et al., 2021; Grzybows ki et al., 2024).

Educational robotics (EP) is an interdisciplinary activity that mainly concerns the sciences of mathematics, information technology and technology (STEM, Science, Technology, Engineering and Mathematics) contributing significantly to the educational process. It is an environment constructed by computers, electronic components and electromechanical programs that work together and aim to explore different areas of knowledge. Instructional robotics is an effective and flexible teaching of learning that encourages learners (pupils, students, adults) to build and control machines using specific programming languages. In other words, it includes technical components and equipment that are programmed with various programming languages to execute various instructions. With the rapid evolution of robotics, robots have gone so far as to simulate human behavior, making people's lives easier and enhancing the advancement of science.

In education it allows students to experience new experiences, combine learning with fun and play, avoiding traditional teaching methods. It promotes a creative enjoyable way of learning while fostering collaboration, confidence, creativity, and resourcefulness. In addition, an important benefit of robotics is that it promotes innovation, developing the algorithmic and critical thinking of trainees, thus changing the learning process, adopting a different way of thinking, shaping opinions and options for their future involvement in various professions directly related to technology.

Educational robotics is not just a tool in the learning process but an entire field of science consisting of smaller scientific fields, while it can interact effectively with the STEAM method, improving the produced educational result. It aims to enhance the learning experience through the creation and implementation of activities where robots and technology play an active role, interacting with students and educators.

Although children's involvement in educational robotics can encourage their later engagement with computer science and STEAM sciences, robotics alone is not enough to lead to high learning outcomes. In order to achieve high learning results, it should work in combination with other sciences (STEAM), while at the same time teaching and learning should be enhanced through specially designed robotic platforms integrated into an appropriate educational framework that will have added learning value but also create an attractive learning environment for students. It is understood that educational robotics is a modern learning tool that offers a dynamic to the learning process and this is understood by the fact that an effort is made to integrate it into education from an early age. Its dynamics are also evident from the many corresponding competitions that exist regarding educational robotics.

The involvement of children with robotics from an early age can make the education of the subject of computer science more attractive and consequently enrich the motivation of students to deal with STEAM sciences either at an early age or even in later life. In contrast to traditional learning, the integration of robotics into the educational process has a different dynamic, broadens students' interest in the lesson, and makes the whole process more interesting for students, helping them develop their talents and their inclination to new technologies.

1.4. Immersive technologies and education

Immersive educational environments, based on cutting-edge technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are particularly effective, due to the engaging experiences they offer, presenting students with interesting

challenges in realistic environments with simulations of real conditions, for experiential learning, increased engagement, and improved performance (Ahmed and Sutton, 2017). 3D digital applications form intensely interactive learning environments, which approach difficult and difficult concepts in a direct and experiential way.

Virtual reality (VR) is the product of interdisciplinary integration, which includes knowledge of optics, computer science, communication, microelectronics, mechanical engineering, and other disciplines. Virtual reality technology is widely used in many industries, especially in construction, entertainment, but also in other fields. Although it is already quite well-known and has been integrated into various disciplines, its application in education is still at an exploratory stage (Bai et al., 2020). VR is based on the principles of constructivist learning (Bani-Salameh et al., 2017). Exposing students to computer-simulated environments can make learning more effective (Chen et al., 2017), and this is because combining real and virtual environments would result in mixed reality, which would provide students with a wide variety of exploration options (Correia et al., 2016). Virtual reality devices have the ability to trick the senses so that the simulated world can be experienced as real.

Unlike virtual reality (VR), which fully immerses users in a simulated environment, augmented reality (AR) enhances the user's perception of existing reality. This is achieved by providing information that can take various forms, including visual elements (such as images, 3D models, and animations) and auditory elements (such as sounds and music). The key feature of AR is its ability to seamlessly blend the real and virtual worlds, creating a new, enhanced, and interactive experience. Examples of the use of AR such as: digital overlays in museum exhibits, interactive textbooks, and even its application in outdoor learning environments, show the breadth and adaptability of this technology. The rapid and continuous technological advancements highlight the importance of AR in education, and its utilization promises even more immersive and personalized learning experiences. The combination of AR with other educational technologies, such as virtual reality (VR), robotics, artificial intelligence (AI), but also its integration into the STEAM method in general, promises even more impressive learning results.

The term mixed reality (MR) refers to the technology that combines the physical and digital worlds, enabling the connection and interaction between real and virtual objects in real-time. This technology is a combination of the two aforementioned technologies, as it incorporates elements of Augmented Reality (AR) and Virtual Reality (VR), shaping a spectrum of experiences ranging from partially augmented environments to fully virtual spaces (MacCallum and Parsons, 2022). Its effective operation requires advanced sensory information interpretation techniques to create a coherent imaginary representation of the real and digital worlds. In this way, students act as creators of digital experiences, experiencing interactive experiences that contribute to a deeper understanding of complex concepts. At the same time, it offers the possibility of interdisciplinary learning and the development of digital skills, which are necessary for the production of innovative and original ideas and the preparation for the competitive modern labor market. (MacCallum, 2021).

In STEAM education, immersive simulations allow students to explore phenomena that are otherwise inaccessible or impractical, to be studied directly and in real environments. They also offer children the opportunity to design, analyze and implement virtual models using 3D modeling software and interactive environments, receiving immediate feedback on their designs without restrictions on physical materials and production processes. For example, these technologies can be used to visualize geometric shapes and relationships in three dimensions, making theoretical concepts more specific and intuitive (Sorby at al., 2016).

Interactive simulations can help students explore complex mathematical functions and graphical representations, leading to a better understanding of their fundamentals.

2. Material and Method

A systematic review of the literature was carried out, through PRISMA, while search engines for scientific articles, such as Google Scholar, Semantic Scholar, Scopus and ERIC (Education Resources Information Center), which are used extensively in academic research, serve different purposes and have a different way of operating, were used for data collection. In this way, key elements and results of research work were summarized and citation charts were used to explore the connections between documents, identifying the most influential references in their field and providing advanced filtering options. In order to achieve the greatest possible focus on the research topic, the literature research was divided into 4 main axes: STEM Education, Artificial Intelligence (A.I), Robotics and Immersive Technologies (AR, VR, MR).

The search for bibliographic sources was carried out in the two aforementioned search engines based on specific keywords. Initially, articles were searched on: STEAM Education and then the search included the terms: Artificial Intelligence, Robotics, Immersive Technologies as well as variations of these terms. Additional sources were sought based on terms such as: Interdisciplinary learning, Educational theories, Experiential learning, Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), Emerging educational technologies, always related to the STEAM education framework. Additional criteria for searching for scientific research and articles were the following: The files must be accessible, written in English, highly impactful, and have been published from 2000 to 2024. The studies selected met all the above criteria and presented the maximum relevance to the research question.

Although the methodology followed ensures a comprehensive, in-depth and comparative study, a number of limitations need to be recognised. The utilization of secondary data means that no primary empirical research, such as interviews or questionnaires, was conducted. Also, given the ever-evolving nature of technological developments, some recent developments regarding STEAM methodology, Artificial Intelligence, Robotics, and Immersive Technologies may not yet be fully reflected in the literature.

3. Results and Discussion

It is generally accepted that the integration of the STEAM method and new technologies in general into the learning process brings about significant changes, which contribute to fostering innovations in teaching and learning (Nwabueze and Isilebo, 2022). This is because, on the one hand, the interdisciplinarity and interdisciplinarity of the course is enhanced, and on the other hand, because the participation and interest of students is enhanced, as teaching becomes more experiential. At the same time, teachers teach based not only on the concept to be taught, but mainly on examples and experiences from children's daily lives (Kulkarni et al., 2022). After all, innovations in teaching are marked by the utilization of multifaceted teaching methods, adapted to modern educational requirements. The STEAM method is the alternative approach to teaching, where various areas of science are utilized with the aim of pluralism and the transformation of thought theory into practice (Burnard and Colucci-Gray, 2019).

STEAM is an interdisciplinary teaching method (Bertrand and Namukasa, 2020). At the same time, it is a tool that helps students solve real-life problems, offering creative solutions (Herro et al., 2019; Khikmiyah et al., 2021), while at the same time supporting the improvement of their technological skills, specifically through activities inside and outside of school, such as video production, digital drawings/sketches, visual tools, etc. At the same

time, it is a playful and fun way to learn the concepts to be taught (Wu et al., 2022), which is student-centered, relating concepts from different sciences, but also knowledge with technology. Children in an interdisciplinary way become familiar with technology, connect theory with practice, but also with their daily lives, acquire motivation for learning, plan, apply practices and solve problems, develop computational and synthetic thinking skills and understand the concepts of algorithms, programming and other scientific concepts, cultivate social skills and generally acquire skills that upgrade personal and professional growth.

The utilization of interdisciplinary teaching methods, using modern digital technologies, offers the possibility of personalizing learning experiences by adapting the educational content to meet the individual needs of each student (Dogan et al., 2023). At the same time, the integration of interactive elements, such as simulations or quizzes, supports learners' engagement and motivation (Aljarrah et al., 2021), while the use of AI-assisted algorithms by teachers helps to analyze student data, such as performance, preferences and learning pace, and to adapt educational content and activities to their individual needs (Baidoo-Anu and Ansah, 2023).

It is therefore understood that the future education of students must be adapted to the new requirements as they arise from modern reality. The strengthening of teaching innovation also requires modern teaching methods, adapted to the modern needs of the student, but also of education in general. STEAM education can provide the right educational framework so that learning is holistic, adaptive, interactive, and technologically enabled not just to keep up with developments, but to shape them.

4. Conclusion

The 4th industrial revolution is characterized by universal digitization and automation, but also by the widespread use of new technologies, creating new increased demands on both the training of human resources and the education system in general. The STEAM (Science, Technology, Engineering, Arts and Mathematics) educational framework is proposed as an alternative consideration to the teaching of cutting-edge subjects: Science, Technology, Engineering, Art and Mathematics. By supporting the transition to a more active learning approach, which promotes a deeper understanding of the theory and principles of these scientific fields, it emerges as a new, promising alternative model of education. The combination of STEAM technology with artificial intelligence, robotics and virtual, augmented and mixed reality, pushed aside traditional teaching and paved the way for modern pedagogical methods, which enhance student initiative, motivation and participation (Hu et al., 2020).

Despite the advantages of STEAM education in enhancing teaching and educational innovation, its integration into the educational context raises a variety of concerns regarding ensuring their effective, fair, equitable, and responsible use. Digital competence and the integration of STEAM in education also requires the appropriate knowledge, skills and attitudes. Unfortunately, although the majority of teachers try to find innovative learning processes, their knowledge of ICT skills and especially the STEAM method, is not always sufficient and there is a tendency not to use innovative processes in their lessons. On the other hand, the high cost of the method in financial and material resources, the risk of addiction to digital media and the lack of the necessary logistical infrastructure to support its application in the learning process, hardware malfunctions or software compatibility problems, are significant problems for its smooth and effective application in the learning process (Deterding et al., 2020; Salcedo et al., 2023).

Also, over-reliance on digital tools can lead children to be more interested in external rewards rather than inherent learning goals (Deterding et al., 2020), causing high competition,

increased and psychological pressure that can negatively impact the mental health and self-esteem of some students (Hamasha et al., 2024). Fostering a balanced pedagogical approach to the use of technology by educators can help alleviate these health concerns and ensure that students benefit from immersive learning experiences without adverse effects.

For the above reasons, the adequate training of the human resources of education is one of the factors for the successful integration of STEAM, but also of new technologies in general in educational practice. The continuous and up-to-date training of teachers will enhance their digital skills, strengthen their confidence in the use of digital tools in their teaching and generally improve the educational framework around the use of new technologies (Hamash et al., 2024).

In summary, for the smooth and effective integration of the STEAM method and by extension technological innovations in education, careful planning, correct and careful alignment with learning objectives, a specific implementation framework and sound pedagogical principles are required. Future research should focus more on exploring the long-term outcomes of the application of these technologies, both in terms of their positive effects on motivation, knowledge retention and skills improvement, and on the development of ethical guidelines and best practices, so that the use of immersive technologies in education helps to ensure their responsible and equitable application (Saputra et al., 2025).

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted. Authors can combine results and discussion if they wish.

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Thermal Refugia within Temperate Habitats: Modelling Microclimate Landscapes to Predict Bird Distribution Responses

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Abstract

Temperate ecosystems are undergoing accelerated warming and increasingly frequent thermal extremes, yet the vulnerability of avian species within these landscapes is not determined solely by broad-scale climate metrics. Rather, the microclimate the fine-scale thermal environment experienced by individual birds in their habitat plays a critical role in mediating exposure, behaviour, and ultimately distributional responses. This paper presents a framework for modelling microclimate landscapes in temperate habitats and applying these models to predict bird distribution responses under climate change. We synthesise empirical evidence linking microclimate heterogeneity and avian population trends, describe methodological approaches for deriving fine-scale thermal layers, and implement a conceptual modelling workflow that integrates microclimate availability, thermal safety margins and habitat connectivity. We illustrate how this framework could be applied in temperate forest and shrub–grassland systems, and discuss how structural habitat features (e.g., canopy complexity, northerly aspects, dense shrubs) may act as thermal refugia. Our review of long-term breeding bird data shows that sites with cooler sub-canopy conditions in structurally complex forests exhibit less negative population trends, supporting the microclimate-buffering hypothesis. We conclude that incorporating high-resolution micro-climate layers into species distribution modelling significantly refines predictions of vulnerability for temperate birds and highlight key management implications: preserving structural complexity, enhancing connectivity of cooler patches, and targeting micro-climate refugia in conservation planning.

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1. Introduction

Temperate ecosystems are facing increasing challenges attributed to global climate change, marked by notable warming trends of approximately 0.2–0.3°C per decade, as reported by the Intergovernmental Panel on Climate Change (IPCC) (Dobrowski, 2011). This trend brings about a rise in the frequency and intensity of extreme heat events, leading to considerable physiological stress on avian species that depend on behavioral and microhabitat adaptations for temperature regulation (Kim et al., 2022). Traditional species distribution models (SDMs), which primarily rely on macroclimatic data such as annual mean temperature and monthly precipitation, often inadequately capture the micro-environmental conditions experienced by individual birds within heterogeneous landscapes (Chardon et al., 2023). Microclimates defined as localized climatic conditions that differ from the broader region play a critical role in mediating how species respond to shifting macroclimatic patterns (Norris et al., 2011). Factors such as habitat structure, topography, and vegetation density profoundly influence microclimatic conditions. In temperate forests, attributes such as canopy height and density can significantly mitigate maximum temperatures, providing crucial thermal refugia during periods of extreme heat (Arx et al., 2013). For example, birds residing in structurally complex habitats in temperate forests may exhibit less adverse population trends than those in simplified or open-canopy environments, reflecting the adaptive advantages afforded by microclimatic buffering (Pradhan et al., 2023). The "microclimate buffering hypothesis" posits that avian species inhabiting micro climatically diverse habitats will likely experience reduced exposure to extreme temperatures. Consequently, these birds may face slower population declines compared to those in uniform habitats (Sunday et al., 2019). This hypothesis is supported by empirical data indicating that birds in varied habitats, characterized by complex vegetation and topographical features, show improved resilience to climatic extremes (Kim et al., 2022). Researchers emphasize the need to incorporate high-resolution microclimate modeling into broader ecological frameworks to accurately assess avian vulnerability and potential distribution responses amid climate change (Chardon et al., 2023). Despite the recognition of microclimate's essential role, relatively few studies have integrated these fine-scale climatic variables into conventional assessments of species distribution or vulnerability (Frenne et al., 2013). Future research should prioritize the integration of microclimatic data with habitat structural metrics and species-specific thermal tolerances, facilitating a comprehensive modeling framework that identifies potential thermal refugia and evaluates population-level responses to environmental changes (Liu et al., 2025). This synthesis not only underscores the importance of localized climate dynamics but also highlights the necessity for adaptive management strategies aimed at preserving biodiversity in temperate ecosystems under the mounting pressures of climate change. The present study focuses on temperate habitats and develops a framework for modelling microclimate landscapes to predict bird distribution responses under climate change scenarios. By focusing on temperate ecosystems and microclimatic variation, this work aims to bridge the gap between macro-climate predictions and the actual thermal landscapes experienced by birds. The approach provides a mechanistic basis for improving forecasts of species vulnerability, identifying priority habitats for conservation, and guiding adaptive management strategies in the face of ongoing climate change.

2. Material and Method

To construct a microclimate-based modelling framework suitable for temperate bird habitats, a comprehensive synthesis of the existing literature and methodological approaches was undertaken. Studies were selected that met the following criteria:

(1) focused on temperate forest, shrubland, or grassland habitats,

(2) incorporated fine-scale microclimate measurements or modelling,

(3) linked microclimate data to bird distribution, abundance, or demographic parameters, and

(4) provided methodological transparency suitable for replication or adaptation.

Data Sources and Study Selection:

Peer-reviewed literature from 2000 to 2025 was surveyed across Web of Science, Scopus, PubMed, and Google Scholar. Priority was given to studies providing high-resolution microclimate datasets, habitat structural metrics, and empirical or modelled relationships with bird occupancy or population trends.

The resulting studies span multiple temperate regions, including North America, Europe, and East Asia, and encompass various habitat types:

- Forests: Old-growth and secondary deciduous forests, mixed coniferous–broadleaf stands.
- Shrublands and Grasslands: Temperate steppe, heathlands, and mosaic landscapes with patches of dense vegetation.
- Riparian and wetland edges: Areas providing structural heterogeneity and potential cooling microhabitats.

3. Results and Discussion

3.1. Empirical evidence of microclimate effects on temperate birds

Microclimate heterogeneity in temperate habitats has gained recognition for its significant impact on avian distribution, behavioral strategies, and population dynamics. Empirical research across varied environments, including forests, shrublands, and grasslands, has demonstrated that fine-scale variations in temperature and humidity serve as buffers against macroclimatic extremes, thereby reinforcing the microclimate buffering hypothesis (Kim et al., 2022). This hypothesis posits that microclimatic diversity allows avian species to adapt behaviorally to changing environmental conditions, offering refuge during periods of extreme heat or cold.

In forest ecosystems, the presence of complex structural features such as varying canopy heights and densities can create localized microclimatic conditions that mitigate temperature fluctuations and humidity levels. Studies indicate that species occupying these heterogeneous environments may show stable or increasing populations compared to those in more homogenized settings (Frey et al., 2016). Microclimates play an essential role in temperate forests by providing localized environmental conditions that differ from the broader regional climate. Structural features of the forest, such as canopy cover, understory vegetation, and topographic variation, create these microclimatic refugia. These refugia help buffer plant and animal populations from extreme temperature and moisture fluctuations associated with climate change. This buffering capacity is crucial for sustaining species diversity and ecological stability in forest ecosystems increasingly affected by global climate shifts.

In shrubland and grassland ecosystems, similar patterns emerge. Research has shown that areas characterized by dense vegetative cover can maintain cooler microclimates, which provide relief to birds during heat extremes. This allows them to optimize their foraging behavior and nesting success (Bernath-Plaisted et al., 2023). This microclimate resilience is crucial for species that rely on specific habitat conditions for breeding and foraging. Studies indicate that birds often shift their nesting and foraging behaviors in response to varying

microclimatic conditions, enabling them to track these subtle changes in their environment (Champlin et al., 2009; Bernath-Plaisted et al., 2025).

Moreover, advancements in microclimate modeling have shown that many avian species, particularly those dependent on forest understoreys, operate within buffered microclimates that differ significantly from macroclimatic conditions. These models underscore the need for conservation strategies that account for microclimatic complexities present in different habitats, as they can provide insights into potential refugia for species facing climate-induced habitat changes (Padmakumar and Joseph, 2022; Stark and Fridley, 2022). As our understanding of forest ecology and climate interactions advances, it is increasingly important to incorporate microclimate dynamics into habitat management and conservation planning. Considering fine-scale climatic variation can enhance the capacity of management strategies to support species persistence under changing environmental conditions. In particular, integrating microclimate data into habitat models and restoration efforts can improve the resilience of avian populations facing future climate scenarios (LeBrun et al., 2016; Coulson et al., 2025).

Despite these insights, there remains a pressing need for further rigorous research that systematically incorporates microclimate data into broad-scale species distribution projections and vulnerability assessments. Doing so is vital for identifying critical habitats that provide microclimatic refuge and for developing adaptive management framework that enhance avian biodiversity conservation in the face of a changing climate (Schwartz et al., 2020).

3.2. Forested habitats

In temperate forest ecosystems, structural components such as canopy height, density, and understory complexity play a crucial role in creating substantial microclimatic variation. Sub-canopy temperature measurements in deciduous and mixed-coniferous forests reveal differences of up to 5–7 °C between exposed forest edges and cooler interior understories during peak summer conditions (Padmakumar and Shanthakumar, 2023). This temperature fluctuation can create unique microhabitats that influence the distribution and population dynamics of avian species. For instance, birds inhabiting structurally complex forests, characterized by denser canopies and stratified understory layers, tend to exhibit higher occupancy rates and more stable population trends compared to species in simpler or homogeneous stands (Davis et al., 2018).

Long-term monitoring efforts of forest passerines have shown an inverse relationship between sub-canopy temperatures and population decline; sites that maintain cooler microclimates are associated with significantly less negative population trends (Padmakumar et al., 2020). This phenomenon highlights the importance of structural complexity in mitigating thermal stress, which can adversely affect avian populations in increasingly warmer climates. Species such as the wood thrush (Hylocichla mustelina) have been observed to preferentially select nest sites within cooler, shaded microhabitats, where canopy cover and leaf litter depth substantially influence nest-site temperatures and subsequent reproductive success (Frenne et al., 2013; Lombaerde et al., 2022).

Similar patterns are documented in European temperate forests, where species such as the European robin (Erithacus rubecula) and wood warbler (Phylloscopus sibilatrix) are known to occupy cooler, densely vegetated microhabitats, particularly during summer months when macroclimatic extremes become pronounced (Zellweger et al., 2019). The canopy structure and composition directly regulate these microclimatic conditions, providing birds with thermal refugia and enhancing local humidity levels, which fosters a conducive environment for nesting and foraging.

As global temperatures rise and climatic extremes become more frequent, understanding and preserving microclimatic heterogeneity within forest ecosystems will be crucial for the conservation of temperate forest avifauna. Maintaining structural complexity in forests can enhance the resilience of avian communities against challenges posed by climate change (Spicer et al., 2020; Ulyshen et al., 2024). Integrating knowledge of microclimatic dynamics into forest management and conservation practices will be essential for ensuring the longevity and stability of avian populations within these vital ecosystems (Barry and Schnitzer, 2021; Giberti et al., 2023).

3.3. Shrubland and grassland habitats

Temperate grasslands and shrublands are characterized by significant microclimatic variation, which is influenced by several factors, including vegetation density, slope aspect, and proximity to water bodies. Research has demonstrated that dense shrub patches or north-facing slopes serve as small-scale refugia, effectively reducing operative temperatures and providing essential thermoregulatory opportunities for avian species (Eastman et al., 2013; Roonjho et al., 2020). For example, in steppe ecosystems, obligate ground-nesting birds, particularly the little bustard (Tetrax tetrax), select cooler microsites for nesting. Their nest survival rates are positively correlated with microhabitat shading and overall vegetation cover, highlighting the ecological importance of these microhabitats (Fa and Funk, 2007; Moradi et al., 2024).

Microclimatic studies have shown that these microhabitats can effectively reduce maximum daytime temperatures by 2–4 °C compared to surrounding open areas. This reduction is critical for mitigating heat-induced stress and mortality among avian populations (Fa and Funk, 2007; Pierce et al., 2016). The occupancy rates and reproductive success of birds are positively impacted when nesting sites are sheltered from extreme temperatures, allowing them to maintain more stable physiological conditions during the critical summer months (Murphy et al., 2013).

Specifically, investigations into the sagebrush songbird complex have revealed that nest-site selection is profoundly influenced by microclimatic conditions. Nests positioned under dense shrubs or within natural depressions experience diminished temperature fluctuations and lower peak temperatures compared to those in more exposed locations. This buffering effect is vital for reducing thermoregulatory stress for both adult birds and their nestlings (Criado et al., 2020; Mancuso et al., 2022).

Moreover, the notion of microclimatic refugia underscores the adaptive significance of microhabitat selection in the context of climate change. Such microhabitats provide critical resources that enable birds to thrive despite fluctuations in macroclimatic conditions. The increasing awareness of these dynamics reinforces the need to incorporate microclimatic considerations into land-use planning and conservation strategies aimed at preserving avian biodiversity in temperate grasslands and shrublands (Zhu et al., 2025; Li et al., 2025).

The role of microclimatic variation in temperate grasslands and shrublands cannot be overstated. It significantly influences avian habitat selection, reproductive success, and overall biodiversity resilience. As climate change continues to exert pressure on these ecosystems, understanding and conserving microclimatic features will be essential for safeguarding avian populations and, more broadly, the ecological integrity of these habitats.

3.4. Topographic influences

Topography plays a critical role in modulating microclimatic conditions within temperate habitats, especially influencing temperature and moisture availability through various elements such as slope inclination, aspect, and elevation. In the northern hemisphere,

north-facing slopes typically exhibit lower maximum temperatures and increased moisture retention relative to south-facing slopes. This difference in insolation creates essential microhabitats for species that are sensitive to thermal extremes (Pandita et al., 2019). For instance, north-facing slopes often maintain cooler, more humid conditions, which favor moisture-loving plant species and can significantly impact local herbaceous and shrub communities (Lin, 2006).

In addition to slope orientation, valley bottoms play an important role in microclimatic regulation. These areas often retain cooler, moister conditions compared to ridge tops, largely due to the accumulation of cold air during nocturnal inversion events and reduced exposure to solar radiation (Kang et al., 2004). This can influence the distribution and occupancy of various avian and terrestrial species, as cooler valley microhabitats provide refuge against high temperatures that may prevail on adjacent ridges (Sørensen et al., 2006; Egli et al., 2007).

A case in point is observed in upland temperate regions where meadow pipits (Anthus pratensis) demonstrate preferential occupancy of north-facing slopes and moist depressions. Their habitat selection reflects a significant reliance on microtopography to maintain thermal refugia, which is vital during warmer seasons when heat stress can impact physiological well-being and reproductive success (Gilliam et al., 2014; Pan et al., 2022). Studies have indicated that the availability of cooler microhabitats within these environments is positively correlated with the stability of local bird populations, highlighting the adaptive significance of microclimatic influences on species distribution and habitat utilization (Berryman et al., 2015).

Topographically controlled differences in microclimate, including variations in soil moisture and temperatures, significantly shape ecosystem dynamics and species interactions within these habitats. For example, moisture availability is closely tied to topographic features, influencing vegetation patterns, seedling establishment, and overall biodiversity in these specialized environments (Regüés et al., 2006; Gutiérrez-Jurado et al., 2013). As climate changes and elevational ranges shift, understanding the nuances of topographically influenced microclimatic variations will be essential for effective conservation and management strategies aimed at preserving avian communities and the ecological integrity of temperate habitats.

3.5. Structural drivers and modelling microclimates

Microclimate heterogeneity is primarily governed by structural habitat features and terrain, both of which can be quantified and integrated into predictive models.

3.6. Canopy and vegetation structure

In forested landscapes, LiDAR-derived data have significantly enhanced our understanding of canopy structure and its impact on microclimatic dynamics, particularly concerning bird habitats. High-resolution measurements of canopy height, leaf area index, and understory density provide crucial insights into how these structural variables correlate with the moderation of sub-canopy temperatures (Kim et al., 2022). Denser canopies, characterized by a complex arrangement of foliage, significantly reduce solar radiation penetration, which in turn limits maximum temperature extremes while enhancing humidity retention within the forest understory (Frey et al., 2016).

The concept of structural complexity is increasingly recognized as vital for thermally sensitive avian species. In simplified or homogeneous forests, birds experience increased physiological stress, lower occupancy rates, and reduced reproductive success due to a lack of available thermal refugia (Betts et al., 2017; Jemal et al., 2020). For instance, avian diversity

studies have demonstrated that structural heterogeneity can predict bird density and species richness, aligning with the "habitat heterogeneity hypothesis" (Mulwa et al., 2012; Smith et al., 2021). Species thriving in rich, multi-layered environments with varied microclimatic niches tend to exhibit better survival and reproductive outcomes compared to those inhabiting monoculture or minimally structured habitats (Akresh et al., 2023).

The implications of structural complexity extend beyond spatial arrangement; they play a critical role in facilitating ecological interactions and resource availability necessary for successful nesting and foraging (Schall et al., 2020; Bitani et al., 2023). Birds that depend on specific structural features frequently adapt their behaviors based on available resources linked to microclimatic conditions. For example, species utilizing dense understory foliage for nesting or foraging benefit from the cooler and more stable microclimates created by robust tree canopies (González-Gómez et al., 2006).

Moreover, the relationship between forest management practices and structural complexity is essential. Thinning or selective logging can modify forest stand structures, enhancing microclimatic variability and resilience to climate disturbances (Menge et al., 2023). Conversely, reduced structural complexity can lead to declines in avian biodiversity as habitat homogenization increases, emphasizing the conservation value of maintaining diverse and structurally complex habitats (Tews et al., 2003; Betts et al., 2017; Smith et al., 2021).

As climate change poses increasing challenges, the need for conservation strategies that prioritize structural heterogeneity in forest management becomes imperative. Such strategies not only support avian populations but also contribute to broader ecological resilience (Jemal et al., 2020; Kim et al., 2022). Efforts to incorporate LiDAR data into conservation planning can inform effective habitat management practices, ensuring that avian species continue to thrive within their ecological niches as environmental conditions evolve (Zellweger et al., 2019; Frenne et al., 2021).

3.7. Shrub density and patch heterogeneity

In open shrubland and grassland habitats, vegetation density plays a crucial role in creating microhabitat variation that effectively moderates thermal extremes. Spatially heterogeneous patches containing taller shrubs, grasses, or dense ground cover provide shaded areas essential for avian species, significantly reducing operative temperatures during hot periods. These shaded microhabitats serve as critical refugia for birds, enhancing their ability to survive under extreme climatic conditions (He et al., 2010).

The connectivity and spatial distribution of these vegetation patches greatly influence bird movement, access to resources, and overall habitat suitability. Birds benefit from the availability of shaded microhabitats, which can mitigate the adverse effects of high temperatures associated with climate warming (Sankey et al., 2013). Greater patch density and spatial configuration can contribute positively to the ecological health of bird populations, allowing for easier access to food and shelter (He et al., 2015). In addition, LiDAR technology has proven valuable in modeling vegetation density and complexity, providing detailed insights into how structural attributes interact with microclimatic gradients (Acebes et al., 2021).

Effective modeling that incorporates variables such as patch density, spatial arrangement, and vegetation height allows for better predictions of avian responses to habitat modifications and climate change scenarios. Such models have been shown to capture microclimatic gradients, enabling researchers and land managers to assess potential impacts on bird populations and to develop conservation strategies that prioritize the maintenance of heterogeneous vegetative structures (Alonso et al., 2019).

The configuration of shrub patches can significantly affect soil moisture retention and surface temperatures, enhancing habitat suitability for avian species. This is particularly important in regions subject to drought or extreme heat, where access to cooler microhabitats can lead to improved survival rates and reproductive success (Rotenberg and Yakir, 2010). The integration of high-resolution data collection methods, such as LiDAR, into ecological research and management plans will further support efforts to conserve avian biodiversity in these dynamic ecosystems, especially under the pressures of ongoing climate change (Cannone et al., 2007).

3.8. Topography and microclimate integration

Topographic variables, such as slope, aspect, and elevation, are vital for accurately modeling microclimate in temperate landscapes. By integrating these topographic indices with habitat structural data, researchers can generate high-resolution microclimate surfaces that provide crucial insights into ecosystem dynamics (Tewksbury et al., 2002). These surfaces enable the calculation of important metrics, including Micro Climate Availability (MCA), which measures the proportion of habitat that falls below a species' upper thermal threshold (Thorne et al., 2023). This metric is crucial for understanding how microhabitats support species under thermal stress, particularly in light of climate variability.

Another key metric is the Thermal Safety Margin (TSM), which represents the difference between operative temperature and species-specific thermal tolerance (Suggitt et al., 2010). This measurement allows researchers to assess how much thermal relief is provided by specific microhabitats, informing conservation strategies focused on vulnerable species. Maintaining a favorable TSM is essential for species' survival, especially as global temperatures rise due to climate change.

Additionally, Refugia Connectivity (RC) quantifies the spatial continuity of cooler microhabitat patches, facilitating assessments of how well these areas can support species migration and resilience (Wolfe et al., 2025). This connectivity is critical for species facing habitat fragmentation and climate-induced alterations, as it promotes movement between cooler refugia, thereby enhancing population stability and genetic diversity (Svancara et al., 2019).

When combined, these metrics enable researchers to predict potential shifts in species distributions under various climate scenarios, identify populations at risk, and prioritize refugia for conservation management. Consequently, this integrative approach not only supports a more comprehensive understanding of ecological processes but also guides effective conservation strategies aimed at mitigating the impacts of climate change on biodiversity (Bartholomée et al., 2024).

3.9. Microclimate modelling workflow

The proposed workflow for modeling bird distributions in temperate habitats under climate change effectively integrates habitat structure, topography, microclimate derivation, and species response. The workflow can be summarized in the following steps:

1. Mapping Habitat Structure: This initial phase employs LiDAR or high-resolution imagery to quantify essential habitat elements, including canopy height, understory density, shrub presence, and ground cover. Accurate mapping of these structures is crucial as they impact the microclimatic conditions experienced by avian species.
2. Deriving Microclimate Layers: By combining the identified habitat structure with topographic variables (such as slope and aspect) and meteorological data, researchers can generate operative temperature surfaces. Validation of these surfaces can be undertaken using

in-situ temperature loggers to ensure precision in microclimate representation, which can inform models relating habitat characteristics and microclimate stability.

3. Linking Bird Data: Data on bird occurrence, abundance, and demographic patterns are then linked to the derived microclimate layers. This linkage can be established through various statistical methodologies, including regression analysis, occupancy models, or species distribution models. Such integration helps elucidate species' responses to the microclimatic variations created by the underlying habitat structure and topography.

4. Forecasting under Climate Change**:** The final step involves downscaling macroclimate scenarios and overlaying the microclimate layers to calculate critical metrics such as MCA, TSM, and RC. These metrics facilitate predictions of potential shifts in occupancy patterns and help identify refuge sites where species may persist amidst changing climatic conditions.

This comprehensive framework allows researchers to incorporate fine-scale environmental heterogeneity into predictive models, thereby improving the ecological realism and accuracy of climate vulnerability assessments.

3.10. Conservation and management implications

Microclimate-informed conservation planning has direct implications for temperate bird habitats:

• Structural Complexity Preservation: Maintaining old-growth stands, layered understory, and shrub density enhances thermal buffering.

• Connectivity of Thermal Refugia: Spatially linked cooler patches facilitate movement, foraging, and breeding, reducing local extinction risk.

• Habitat Restoration and Management: Thinning, selective planting, or shrub restoration can enhance microclimate availability and buffer against warming.

• Site Prioritisation: Areas predicted to maintain low operative temperatures under future climates should be prioritised for protection or restoration.

By integrating microclimate data into management strategies, conservation practitioners can more effectively mitigate the impacts of climate change on temperate bird communities.

3.11. Research gaps and future directions

Despite advances, several knowledge gaps remain:

1. Temporal Resolution: Most microclimate studies capture daily or seasonal variation, but diurnal and extreme-event dynamics are underrepresented.

2. Species-Specific Thermal Limits: Limited empirical data constrain calculation of TSM for many temperate bird species.

3. Mechanistic Links: Direct connections between microclimate exposure and vital rates (survival, reproduction) require more empirical study.

4. Dynamic Habitat Change: Modelling microclimate in conjunction with habitat alterations (logging, shrub encroachment, fire) is needed for realistic forecasting.

5. Integration with Demography: Incorporating population dynamics and dispersal into microclimate-based models can improve predictions of species persistence.

Addressing these gaps will strengthen the predictive power of microclimate-informed models and enhance conservation strategies for temperate avifauna.

4. Conclusions

Temperate bird species are increasingly exposed to climatic stressors, including rising temperatures and more frequent heatwaves. Traditional macro-climatic assessments often fail

to capture the nuanced thermal environments experienced by birds at the scale of their habitats. This study highlights the critical role of microclimate heterogeneity in mediating avian responses to climate change and provides a structured framework for integrating fine-scale environmental variation into predictive models of bird distribution.

Empirical evidence demonstrates that structural complexity in temperate habitats — including canopy height, understory density, shrub cover, and topographic variation — creates localised thermal refugia. Birds exploiting these cooler microhabitats exhibit more stable population trends, enhanced reproductive success, and greater resilience to temperature extremes. In forests, dense canopy layers and layered understories reduce operative temperatures, whereas in grasslands and shrublands, patchy vegetation and north-facing slopes offer essential cooling refuges. These findings collectively support the microclimate buffering hypothesis, underscoring the importance of considering fine-scale environmental variation when assessing species vulnerability.

The proposed workflow integrates habitat structure mapping, microclimate derivation, bird data linkage, and forecasting under future climate scenarios. Key conceptual variables, including Microclimate Availability (MCA), Thermal Safety Margin (TSM), and Refugia Connectivity (RC), enable researchers and conservation practitioners to identify thermally suitable habitats, anticipate distributional shifts, and prioritise areas for protection or restoration. By explicitly incorporating microclimatic information, this approach improves the ecological realism of species distribution models and provides actionable insights for conservation planning.

From a management perspective, several strategies emerge. Maintaining or restoring structural complexity, ensuring connectivity between cooler habitat patches, and targeting conservation interventions towards areas predicted to retain favourable microclimates under warming scenarios are critical. Restoration activities should consider both vertical (canopy, understory) and horizontal (patch connectivity) structural heterogeneity to maximise thermal buffering capacity. Monitoring programs should integrate fine-scale temperature measurements with demographic and occupancy data to assess the effectiveness of conservation interventions and refine predictive models over time. Despite these advances, significant research gaps remain. High-resolution microclimate datasets are limited for many temperate regions, and species-specific thermal tolerance data are often lacking. Additionally, temporal dynamics, such as diurnal temperature variation and extreme events, are underrepresented in most studies. Integrating demographic data, dispersal mechanisms, and dynamic habitat changes into microclimate-based models represents a promising frontier for future research. Such integrative approaches will be essential for accurately forecasting species persistence and informing adaptive conservation strategies in the face of ongoing climate change. Therefore, microclimate modelling offers a powerful lens for understanding and predicting bird responses to environmental change in temperate habitats. By recognising the importance of localised thermal refugia and habitat heterogeneity, ecologists can refine vulnerability assessments, improve predictive accuracy, and guide conservation efforts more effectively. As climate change continues to reshape ecosystems, the adoption of microclimate-informed frameworks will be pivotal in ensuring the persistence of temperate bird species and the maintenance of functional and biodiverse avian communities.

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The Dichotomy of Chromium as Essential Micronutrient Versus Toxic Substance A Review

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Abstract

Chromium functions as a cofactor for insulin, thereby influencing the metabolism of carbohydrates, proteins and lipids. Chromium deficiency has been associated with various clinical conditions, including glucose intolerance, elevated circulating insulin levels, glycosuria, growth disorders and hypoglycaemia. Among the two most prevalent oxidative states of chromium, trivalent chromium (Cr^{3+}) is considered beneficial, whereas hexavalent chromium (Cr^{6+}) is recognized for its toxicity, including carcinogenic effects. Several vegetables, such as broccoli, and fruits, such as grapes, naturally contain high levels of chromium; however, chromium supplements are increasingly popular, primarily due to their purported role in weight loss. Excessive intake of chromium may result in anaemia, thrombocytopenia, liver diseases and renal failure. The toxicity of chromium can potentially be mitigated by certain compounds, such as N-acetylcysteine (NAC) and herbal remedies, such as *Moringa oleifera* leaf extracts. The role of chromium in biological systems remains incompletely understood, necessitating further research.

Review Article

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Chromium,
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1. Introduction

Chromium, a trace element comprises approximately 0.01% or 100 ppm of the Earth's crust (Emsley, 2001) and is naturally found in many foods that we consume. The two prevalent oxidation forms of Cr are trivalent chromium (Cr^{3+}) and hexavalent chromium (Cr^{6+}). The trivalent form is considered a beneficial micronutrient whereas hexavalent chromium has no known biological functions and is a potent carcinogen. The major environmental and health–related challenges of Cr, however, are predominantly due to anthropogenic activities. The production of world annual Cr, as chromite ore (Cr_2O_3), was estimated at 44 million tons in 2019 (the dominant producing countries were South Africa, Turkey, Kazakhstan, and India) (U.S. Geological Survey, 2020). The major sources of Cr in the environment are the electroplating and metal finishing industries, chemical plants, iron and steel factories, tanneries, and textile manufacturers (Ecological Analysts, 1981).

Chromium does not play any significant role in plant physiology (Dixit et al., 2002). However, Cr has been found to be essential for normal carbohydrate and lipid metabolism in mammals and birds. chromium is thought to be a cofactor for insulin activity (Anderson, 1981). In fish, Cr salts have been reported to assist glucose consumption and hinder gluconeogenesis (Hertz et al., 1989). Shiau and Lin (1993) have revealed that supplemental dietary Cr boosts weight gain, energy deposition, and liver glycogen content in tilapia fed with elevated glucose diets.

Accumulation of Cr by plants could decrease growth and pigment content, stimulate chlorosis, and damage root cell (Panda and Choudhury, 2005). Plants collect Cr from nutrient solution thus, higher levels of Cr concentration can be found in plants collected from high–Cr rich soils than that low–Cr soils. However, plants generally retained Cr in the root systems than in above–ground parts (Cary and Kubota, 1990). Metabolic alterations by Cr exposure have also been described in plants (Shanker et al., 2005).

The function of chromium in humans varies with exposure route, oxidation state, and chemical composition (Moffat et al., 2018). The objective of the present review is to consider both the beneficial role and toxic effects of chromium.

1.1. Chemical nature of chromium

The relative atomic mass of chromium is 51.996 g. Theoretically; it may exist in oxidation states from –2 to +6. However, Cr has been noted to show oxidation states of 0, +2, +3 and +6. Elemental Cr (0) is not found readily in the earth's crust. Divalent chromium (Cr^{2+}) is unstable in nature and is easily oxidised into trivalent chromium (Cr^{3+}). Trivalent chromium (Cr^{3+}) is the most stable oxidation form of Cr, hence, shows the lowest reactivity. Hexavalent chromium (Cr^{6+}) is less stable than trivalent chromium (Cr^{3+}). It shows strong oxidising activity in an acidic medium. Mention may be made that most of the biologically occurring Cr are trivalent chromium (Cr^{3+}) while hexavalent chromium (Cr^{6+}) is of industrial origin. Compounds of chromium which are most abundant include halides, oxides, and sulphides (Pechova and Pavlata, 2007).

1.2. Biological nature of chromium

Elemental Cr (0) is biologically inert while divalent chromium (Cr^{2+}) due to its unstable nature is not found in biological systems. Trivalent Cr, the most stable form of chromium is readily found in biological systems, however, it cannot cross the cell membrane easily. Phagocytic processes or nonspecific diffusion assist Cr^{3+} to cross the cell membrane. Trivalent Cr has been reported as an essential micronutrient for humans having multifarious biological functions. On the other hand, Cr^{6+} very easily crosses cell membranes and has toxic effects including cancer (Monga et al., 2022).

1.3. Chromium in a biological system

Both inorganic and organic chromium may enter the biological system mainly through diet. The absorption of Cr in the body is inversely proportional to the dose. The intestine is the main site for chromium absorption. Chromium absorption is influenced by many factors including carbohydrates, proteins, chelating elements, and metals. Unabsorbed Cr is mainly excreted by faeces while absorbed Cr is chiefly excreted via urine. Absorbed Cr may be retained in cells or may circulate in blood upon binding with molecules like beta globulin and transferrin (Krejpcio, 2001; Monga et al., 2022).

1.4. Normal chromium level in human body and results of deficiency

The amount of Cr in human blood and tissues has been reported to vary widely in different studies. Until 1978 levels of Cr in blood were claimed to range between 1 and 40 μg/l (Veillon and Patterson, 1999). In a later study, it was reported that the concentration of Cr in blood serum was 0.035–0.04 μg/l while that for full blood it was 0.120–0.34 μg/l for a healthy human population (Christensen, 1993). Dubois and Belleville (1991) have reported that the normal human body contains total chromium concentration in the range between 0.4 and 6 mg. Among the different tissues and organs Cr tends to accumulate in epidermal tissues like hair, and in bones, kidney, liver, adrenal gland, spleen, lung and in the intestine[12]. Symptoms of Cr deficiency in humans include glucose intolerance, increased circulating insulin, glycosuria, growth disorders, hypoglycaemia, increased serum cholesterol and triacylglycerols, neuropathy, encephalopathy, increased intraocular pressure, reduced number of insulin receptors, reduced muscle proportion, low respiratory quotient, abnormal nitrogen metabolism, and increased proportion of body fat (Anderson, 1994).

2. Biological role of chromium

Researchers around the globe have performed several studies to demonstrate the biological role of chromium. Most of these studies have been based on Cr deficient diet and /or with Cr supplements. A few of the major thrust areas that have gained much popularity are discussed below.

2.1. Carbohydrate metabolism

It has long been postulated that Cr has a role in carbohydrate metabolism by potentiating insulin action. However, the actual mode of action is not yet known. It has been proposed that insulin action is promoted upon binding of chromodulin (a low molecular weight Cr binding oligopeptide) to insulin receptors and in turn, activating it (Eckhert, 2014). Researchers have found that Cr supplementation can influence human glucose tolerance and insulin resistance (Anderson, 2000; Tuzcu et al., 2014). Further, it has been found that Cr supplementation along with insulin can result in increased glucose utilization by means of glucose oxidation and glycogenesis along with the conversion of glucose to lipids (Anderson, 1997).

2.2. Protein metabolism

The role of Cr in protein metabolism has been studied by various researchers. It has been reported that Cr plays important role in the usage of amino acids. Moreover, it has been shown that Cr facilities the absorption, transport, and storage of amino acids. Also, Cr has been identified to influence the intracellular movement of amino acids thereby facilitating the synthesis of protein molecules (Tao, 2019). It has been reported that the addition of chromium can increase protein levels in blood plasma.

2.3. Lipid metabolism

Cr–picolinate has been reported to be widely used in weight loss programs and in an increase of lean body mass. Also, Cr supplementation has been reported to decrease total cholestanol and triglycerides along with LDL cholesterol and non–esterified fats in blood serum. However, this supplementation has also been reported to increase HDL cholesterol in serum (Lai et al., 2006).

2.4. Nucleic acid metabolism

It has been reported that Cr has a very strong affinity for nucleic acid and can help in maintaining the structural integrity of nucleic acid. Reports have been made that Cr can bind to chromatin and influence gene expression. Heat denaturation of RNA has been proposed to be protected by Cr. Also, it has been found that Cr can increase in vitro RNA synthesis (Okada et al., 1989).

2.5. Mineral substances metabolism

Transferrin is the molecule that binds both Fe and Cr. However, this binding is antagonistic (Sayato et al., 1980). Alteration in Fe homeostasis and impaired Fe metabolism along with decreased tissue Fe have been correlated with Cr supplementation (Anderson et al., 1996). In other studies, Cr has been found to interfere with the metabolism of several minerals including Al, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, P, Pb, Se, Sr, V, and Zn (Frank et al., 2000a; Frank et al., 2000b).

2.6. Hormonal regulation

Chromium supplementation has been proposed to influence the functioning of several hormones including cortisol and insulin (Pechova and Pavlata, 2007), however, the exact pathway in which these reactions occur is mostly unknown.

2.7. Role on growth, body composition, and reproduction

Studies have shown a positive correlation between Cr supplementation and weight gain during stressful conditions in cattle and pigs. Also, in some studies increases in muscle content have been reported. However, there are reports of having no influence or negative influence on body weight and muscle as well. However, chromium picolinate has been used in humans to lose weight. Reproductive success with Cr supplements has been studied by various researchers and it was found that the use of these supplements could increase litter size in pigs. On the other hand, Cr–deficient diets have been reported to reduce sperm count and lower the fertility of the sperm in rats (Pechova and Pavlata, 2007).

2.8. Role on immunology

Studies with cows and pigs have shown that Cr supplementation can increase antibodies for certain pathogens. Again, Cr deficiency has been found to be influencing haematological parameters (Pechova and Pavlata, 2007).

2.9. Role on life span

Studies with mice having Cr supplement treatment have been found to show a low mortality rate and higher longevity (Evans and Meyer, 1992). Studies with broilers have also shown lower mortality rates when treated with Cr supplement (Hossain et al., 1998). The antiaging property of Cr has been postulated to be related to its effect on insulin.

3. Toxicological Effect of Chromium

It is generally thought that trivalent chromium (Cr^{3+}) is beneficial while hexavalent chromium (Cr^{6+}) is toxic. However, recent findings have shown that Cr^{3+} can also have toxic effects mainly depending on the dosage. A brief discussion on the toxicity of both Cr^{3+} and Cr^{6+} has been given below.

3.1. Toxic effects of Cr^{3+}

Studies have shown that Cr^{3+} can interact with DNA to damage it. However, the low penetration ability of Cr^{3+} through cell membranes has made it less toxic. Overdosing of Cr may lead to adverse conditions as has been found in few studies. These include loss of weight, anaemic conditions, deficiency of platelets in the blood, liver diseases, renal failure, breakdown of muscle tissue, skin problems, and hypoglycemia (Fowler, 2000; Vincent, 2003). However, Cr^{3+} consumed through a normal daily diet has seldom been found to exert toxic effects, in fact, the toxicity of Cr^{3+} has been found to be less than essential elements like Cu, I, Zn, Mn, and Se (Lindemann, 1996). The dietary intake safe limit for Cr^{3+} has been set at 50–200 mg/day (Monga et al., 2022).

3.2. Toxic effects of Cr^{6+}

The penetrance of Cr^{6+} is much higher than Cr^{3+} through the cell membrane. Mention may be made that inside the biological cell Cr^{6+} can be converted to Cr^{3+} through the Fenton reaction and during this conversion harmful reactive oxygen species (ROS) like hydrogen peroxide, hydroxyl radicals, and superoxide anion radicals are produced (Genchi et al., 2021) that can have deleterious effects on cell and cellular organelles including irreversible DNA damage, tissue necrosis, and cancer (Pavesi and Moreira, 2020). Among specific organs, Cr^{6+} has been reported to damage and cause cancer to the skin, lungs, liver, kidney, and brain along with impaired immune system and reproductive system (Monga et al., 2022).

4. Remedy for Cr^{6+} Toxicity

Like many other toxic substances, microbiota in the gut acts as the first line of defense. Consuming tailored probiotics can help remediate Cr^{6+} toxicity to a great extent (Wu et al., 2017; Ming et al., 2020). Chelation treatment with N– acetylcysteine (NAC) has been found to be beneficial against Cr^{6+} toxicity (Poonam et al., 2018). However, treatment with chemicals has certain side effects. Hence the use of herbal medicines to cure heavy metal toxicity has been proposed (Mehrandish et al., 2019). *Moringa oleifera* leaf extracts and mushrooms like *Pleurotus tuberregium* and Curcumin are worth mentioning in this regard (Monga et al., 2022).

5. Sources of Chromium

Chromium supplements are gaining popularity day by day and according to a report in the United States the sales for Cr^{3+} supplement was estimated at $110 million in the year 2016 (Monga et al., 2022). However, there are several natural food sources that can sufficiently meet the need for Cr required for the normal functioning of the body. Broccoli has a high content of Cr, and other vegetables like Potatoes, Green beans, tomatoes, Celery, and Carrots are rich sources of Cr. Among fruits Grapes have been reported to contain a high amount of Cr also, fruits like Apple, Orange, Banana, and Orange are good sources of Cr. Some of the spices and herbs are rich sources of Cr. These include Basil leaves, Turmeric, Oregano, Pepper, Mint, Garlic, and Saffron. Dairy products like Butter and Margarine also contain a good quantity of Cr (Dattilo and Miguel, 2003).

6. Conclusions

Studies have shown that Cr plays role in carbohydrate, protein, lipid and nucleic acid, and other mineral substance metabolism. Also, Cr has been clinically correlated with body weight change, lean mass increase, growth, and reproduction modulator along with immunity booster. Cr may also act as an antioxidant (Anderson and Cefalu, 2010). However, the precise mode of action of Cr action is mostly unknown. Based on chromium's effects on insulin action the Food and Nutrition Board (FNB) of the U.S. food supply in 2001 considered Cr as an essential nutrient (Institute of Medicine, Food and Nutrition Board, 2001). However, most recent findings have shown that any abnormalities caused due to deficiency of Cr are not readily cured upon treatment with Cr, hence, many have raised the question of whether Cr should at all be considered an essential mineral. Accordingly, the European Food Safety Authority Panel on Dietetic Products, Nutrition, and Allergies in the year 2014 has commented that since there has been no conclusive evidence that Cr is an essential nutrient and therefore, setting recommendations for Cr intake would be inappropriate (EFSA NDA Panel, 2014).

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Saksıda Yetiştirilen Süs Bitkilerinde Yabancı Otların Tespiti: Artvin Çoruh Üniversitesi Fidanlığı

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Özet

Bu araştırma, Artvin Çoruh Üniversitesi Fidanlığı'nda saksıda yetiştirilen süs bitkilerinin üretim alanında görülen yabancı ot türlerini belirlemek, yoğunluk ve yaygınlıklarını saptamak ve elde edilen verilere dayalı olarak sürdürülebilir yabancı ot yönetim stratejileri geliştirmek amacıyla yürütülmüştür. 2024–2025 yıllarında gerçekleştirilen çalışmada, toplam 23 familyaya ait 64 yabancı ot türü tespit edilmiştir. En yüksek tür oranları %20,31 ile Asteraceae ve %17,19 ile Poaceae familyalarına ait olup, baskın türler arasında *Portulaca oleracea* L., *Cynodon dactylon* (L.) Pers., *Polygonum aviculare* L., *Conyza canadensis* L., *Sinapis arvensis* L., ve *Setaria verticillata* (L.) P.Beauv., *Heliotropium europaeum* L., *Polygonum aviculare* L. yer almaktadır. Belirlenen türlerin yoğunlukları 10,1–13,5 adet/m^2 arasında değişmektedir. Bu durum, fidanlık üretim alanlarında baskın yabancı otların süs bitkileri üzerinde ciddi bir rekabet baskısı oluşturduğunu ortaya koymaktadır. Araştırma bulguları, yabancı ot yönetiminde özellikle baskın ve yüksek rekabet gücüne sahip türlere odaklanılması gerektiğini göstermektedir. Bu bağlamda, yabancı otların yol açtığı mevcut sorunların azaltılabilmesi için entegre mücadele uygulamalarına öncelik verilmesi büyük önem taşımaktadır. Söz konusu yaklaşım, baskın yabancı otların etkin biçimde kontrolünü sağlarken, süs bitkilerinin kalite ve verim düzeylerinin korunmasına katkıda bulunmakta ve fidanlık üretiminde sürdürülebilir, çevre dostu ve ekonomik açıdan verimli uygulamaların geliştirilmesi için sağlam bir bilimsel temel oluşturmaktadır.

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Detection of Weeds in Potted Ornamental Plants: Artvin Çoruh University Nursery

Abstract

This research was conducted to identify the weed species found in the production area of ornamental plants grown in pots at Artvin Çoruh University Nursery, to determine their density and prevalence, and to develop sustainable weed management strategies based on the data obtained. In the study, carried out in 2024–2025, a total of 64 weed species belonging to 23 families were identified. The highest species percentages belonged to the Asteraceae family with 20.31% and the Poaceae family with 17.19%. Dominant species included *Portulaca oleracea* L., *Cynodon dactylon* (L.) Pers., *Polygonum aviculare* L., *Conyza canadensis* L., *Sinapis arvensis* L., *Setaria verticillata* (L.) P.Beauv., *Heliotropium europaeum* L. and *Polygonum aviculare* L. The densities of the identified species ranged from 10.1 to 13.5 individuals/m^2. This situation reveals that dominant weeds in nursery production areas create significant competitive pressure on ornamental plants. Research findings indicate that weed management should focus particularly on dominant and highly competitive species. In this context, prioritizing integrated pest management practices is crucial to mitigate the current problems caused by weeds. This approach effectively controls dominant weeds, contributes to maintaining the quality and yield levels of ornamental plants, and provides a solid scientific foundation for developing sustainable, environmentally friendly, and economically efficient practices in nursery production.

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1.Giriş

Süs bitkileri, hem doğal hem de yapay peyzajların estetik değerini artıran ve çevre düzenlemelerinde yaygın olarak kullanılan bitkisel materyaller olarak büyük önem taşımaktadır (Karagüzel ve ark., 2010; Külek ve Beyhan., 2024). Küresel ölçekte süs bitkileri sektörü, ekonomik getirisi yüksek ve istihdam sağlayan önemli bir tarım alt sektörü olarak hızla büyümektedir (Ay, 2009; Erdemir, 2014, Torun ve Can, 2014). Türkiye'de son yıllarda süs bitkileri üretimi ve tüketiminde belirgin bir artış yaşanmakta olup, özellikle saksıda yetiştirilen süs bitkilerinin pazar payı hızla genişlemektedir (Ay, 2009; Torun ve Can, 2014; Küçük, 2019; Yılmaz ve Yıldız, 2020; Küçük ve ark., 2022). Bu bağlamda, süs bitkisi üretiminin verimliliği ve kalitesi üzerinde etkili olan başlıca biyotik etmenlerden biri de yabancı otlardır.

Yabancı otlar, kültür bitkileriyle aynı ekolojik nişi paylaşan ve su, besin, ışık ile alan gibi kaynaklar için rekabet eden ve bitki gelişimini doğrudan olumsuz etkilemektedir (Odum, 1971; Uygur ve ark., 1984; Özer ve ark., 2001; Güncan, 2019). Özellikle saksı süs bitkilerinde toprağın sınırlı ve kapalı olması, yabancı otların oluşturduğu rekabetin çok daha yoğun ve zararlı olmasına neden olmaktadır. Ayrıca yabancı otların gelişimi, süs bitkilerinin estetik görünümünü bozmakta, üreticiye ek iş gücü ve maliyet yüklemekte, ürün kalitesini ve pazarlanabilirliğini düşürmektedir (Uluğ ve ark., 1993; Roul ve Lemay, 2000; Case ve ark., 2005; Kaçan ve ark., 2018). Bu nedenle, yabancı otların etkili biçimde kontrol altına alınması, süs bitkileri üretiminin sürdürülebilirliği ve verimliliğinin korunması açısından büyük önem taşımaktadır. Yabancı otların biyolojik çeşitliliği ile yoğunluk düzeylerinin bilimsel ve nesnel yöntemlerle doğru biçimde belirlenmesi, sürdürülebilir ve etkin kontrol stratejilerinin geliştirilmesinde temel bir başlangıç aşamasını oluşturmaktadır (Önen ve Özer, 2001; Akça ve Işık, 2016; Sırrı, 2019). Bu süreçte, sahada yapılan sürvey çalışmalarıyla yabancı otların tür bazında tespiti, yaygınlık ve yoğunluklarının hesaplanması gerekmektedir. Ayrıca, bölgesel farklılıkların göz önünde bulundurulması, yabancı ot yönetiminde başarıyı artırmaktadır (Tepe, 1989). Saksı ortamında süs bitkisi yetiştiren işletmelerde, yabancı otların kontrolü genellikle iş gücü kullanılarak sağlanmaktadır; ancak saksılı üretim alanlarında uygulanan elle temizleme yöntemi, hem zaman alıcı hem de maliyetli olması nedeniyle üreticiler açısından ciddi bir sorun teşkil etmektedir (Roul ve Lemay, 2000; Küçük, 2019). Bu kapsamda, Artvin gibi Karadeniz'in nemli ve serin iklim özelliklerine sahip bölgelerinde yapılan araştırmalar, bölgeye özgü yabancı ot türlerinin belirlenmesi ve etkin mücadele yöntemlerinin geliştirilmesi açısından önem arz etmektedir. Türkiye'de, özellikle Karadeniz Bölgesi'nde saksı süs bitkileri üretiminde yabancı otlarla mücadeleye yönelik yapılan çalışmaların sayısı oldukça sınırlıdır. Bu alandaki bilgi eksikliği, bölgesel koşullara uygun etkili yönetim stratejilerinin geliştirilmesini zorlaştırmaktadır. Bu ihtiyacı karşılamak amacıyla, Artvin Çoruh Üniversitesi Fidanlığı'nda gerçekleştirilen bu araştırma, saksıda yetiştirilen süs bitkilerinin üretim sahasında görülen yabancı ot türlerinin tespit edilmesi, bu türlere ait yoğunluk ve yaygınlık bilgilerinin ortaya konması ve elde edilen bulgular doğrultusunda sürdürülebilir yabancı ot yönetimi stratejilerinin geliştirilmesi amaçlanmıştır. Elde edilen bulguların, bölgesel üreticilere ve akademik çalışmalara katkı sağlayarak sürdürülebilir üretim uygulamaları ve çevre dostu yönetim prensiplerinin benimsenmesine önemli bir temel oluşturması beklenmektedir.

2. Materyal ve Yöntem

Bu çalışma, 2024–2025 yıllarında Artvin Çoruh Üniversitesi yerleşkesi içerisinde bulunan fidanlık alanında yürütülmüştür. Çalışmanın materyalini, fidanlıkta 28×28 cm ebatlarındaki saksılarda yetiştirilen toplam 1.000 adet süs bitkisi ile bu bitkiler arasında doğal olarak gelişen yabancı ot türleri oluşturmuştur. Saksılarda kullanılan yetiştirme ortamı; perlit,

torf, hayvan gübresi ve toprak karışımından meydana gelmektedir. Yabancı ot türlerinin yaygınlık (%) ve yoğunluk değerlerinin belirlenmesi amacıyla rastgele örnekleme yöntemi uygulanmıştır (Uluğ ve ark., 1993). Çalışma alanını temsil edecek şekilde, toplam bitki sayısının yaklaşık %10 karşılık gelen 100 saksı rastgele seçilmiş ve her bir saksı bir örnekleme birimi olarak değerlendirilmiştir. Örnekleme sayısı, literatürde önerilen minimum tekrar sayıları dikkate alınarak belirlenmiştir (Kent, 2011). Dikotiledon yabancı otlar belirlenirken tüm bitki olarak, monokotiledon yabancı otlar ise sap olarak sayılmıştır (Öğüt ve Boz, 2007). Toplanan örnekler, tür teşhisinin doğrulanması amacıyla Artvin Çoruh Üniversitesi Orman Fakültesi Herbaryumu'nda muhafaza edilmiştir. Tür teşhisleri ve adlandırmalarında; Davis (1985–1988), Uluğ ve ark. (1993), Baytop (1997), Özer ve ark. (2002) ile Plants of the World Online (Anonim, 2025) adlı yayınlar ve veri tabanı esas alınmıştır. Yabancı ot türlerinin yaygınlık (%) değerleri, bir türün görüldüğü örnekleme birimi sayısının toplam örnekleme birimi sayısına oranlanmasıyla; yoğunluk değerleri ise toplam birey sayısının toplam örnekleme birimi sayısına bölünmesiyle hesaplanmıştır (Odum, 1971).

Yaygınlık (Y, %): Bir türün örneklenen alanlarda görülme oranını yüzdesel olarak ifade eder.

Formül: $Y(\%)=n/m\times100$

Burada,

n: Belirli bir türün gözlendiği örnekleme alanı sayısı,

m: Toplam örnekleme alanı sayısıdır.

Genel Yoğunluk (GY, adet/m²): Bir türün birim alan (m²) başına düşen birey sayısını ifade eder.

Formül: $GY=TS/m$

Burada,

TS: Bir türün tüm örnekleme alanlarında saptanan toplam birey sayısı,

m: Toplam örnekleme sayısıdır.

Fidanlık üretim alanlarında saptanan yabancı otlar, yaygınlık ve yoğunluk değerlerine göre kategorilere ayrılmış ve böylece sahada baskın olan türler belirlenmiştir. Bu sınıflandırma, daha önceki çalışmalarda geliştirilen yöntemler (Tepe, 1989; Uludağ, 1993; Arslan, 2018) doğrultusunda oluşturulan skala esas alınarak yapılmıştır (Tablo 1).

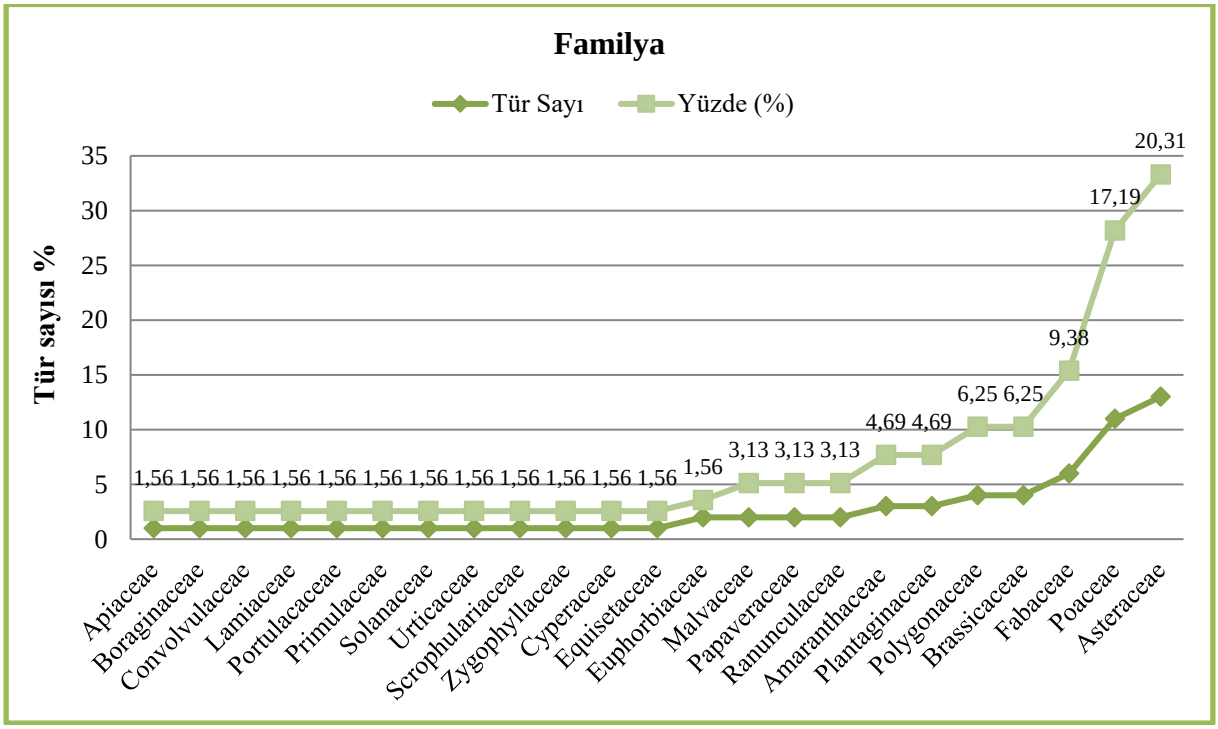
Tablo 1. Türlerin yaygınlık ve yoğunluk değerlerine göre gruplandırılmasında başvurulan ölçekler

Yaygınlık skalası	Yoğunluk skalası
Çok yaygın (Ç): ≥ %50	Çok yoğun (A): ≥ 10 adet/m²
Yaygın (Y): %25–49	Yoğun (B): 5,00–9,99 adet/m²
Orta yaygın (O): %13–24	Orta yoğun (C): 1,00–4,99 adet/m²
Düşük yaygın (N): < %12	Düşük yoğun (D): 0,10–0,99 adet/m²
	Çok düşük yoğun (E): 0,01–0,09 adet/m²
	Nadir (F): < 0,01 adet/m²

3. Bulgular

Artvin Çoruh Üniversitesi fidanlığında yürütülen bu çalışmada, iç ve dış mekân süs bitkisi üretiminde kullanılan saksılarda gelişen yabancı ot türleri belirlenmiş ve familyalara göre dağılımları incelenmiştir. Yapılan araştırma sonucunda, iç ve dış mekânlarda süs bitkisi yetiştirilen saksılarda 23 farklı familyaya ait toplam 64 yabancı ot türü belirlenmiştir. Tür

sayısı bakımından en yüksek oranlar Asteraceae (%20,31) ve Poaceae (%17,19) familyalarında belirlenmiş olup, bu familyaların toplam türlerin önemli bir kısmını oluşturduğu ve çalışma alanında baskın olduğu tespit edilmiştir. Fabaceae (%9,38), Brassicaceae (%6,25) ve Polygonaceae (%6,25) familyaları yüksek oranlarda temsil edilirken, diğer familyalar ise %1,56–3,13 aralığında değişen daha düşük oranlarda yer almıştır. Benzer şekilde, süs bitkisi üretim alanlarında yapılan farklı çalışmalarda da bu familyaların yoğun şekilde görüldüğü bildirilmiştir (De Mol ve ark., 2015; Küçük, 2019; Küçük ve ark., 2020; Küçük ve ark., 2022) (Şekil 1).



Şekil 1. Süs bitkisi üretiminde saksılarda belirlenen yabancı ot familyalarının tür sayısı (%)

Fidanlık üretim alanında yapılan çalışmada, iç ve dış mekân süs bitkisi üretim sahasında 23 farklı familyaya ait toplam 64 yabancı ot türünün morfolojik incelemeleri sonucunda, bu türlerden 12 tanesi monokotiledon, 51 tanesi dikotiledon ve 1 tanesi ise tohumsuz olduğu saptanmıştır. İç ve dış mekân üretim alanında rastlanan yabancı otların yoğunluk (adet/m^2) ve yaygınlık (%) değerleri ise ayrıntılı olarak Tablo 2'de verilmiştir.

Fidanlık üretim alanında yürütülen bu çalışmada, Tablo 2'de sunulan türlerin yaygınlık ve yoğunluk değerleri değerlendirildiğinde, özellikle Asteraceae ve Poaceae familyalarının alanda baskın konumda olduğu belirlenmiştir. Özellikle *Conyza canadensis* L., *Capsella bursa-pastoris* (L.) Medik., *Sinapis arvensis* L., *Heliotropium europaeum* L., *Trifolium pratense* L., *Convolvulus arvensis* L., *Cynodon dactylon* (L.) Pers., *Setaria verticillata* (L.) P.Baeuv., *Polygonum aviculare* L. ve *Portulaca oleracea* L. türlerinin %100 yaygınlık oranına ve 10 adet/m^2'yi aşan yoğunluk değerlerine sahip olması, söz konusu türlerin alanda baskın yabancı otlar olduğunu ortaya koymaktadır (Yu ve Marble., 2022; Altland ve ark., 2023).

Tablo 2. İç ve dış mekân süs bitkisi üretiminde kullanılan saksılarda gözlenen yabancı ot türlerinin yaygınlık ve yoğunluk değerleri

Familyası	Latincesi	Türkçe	Yaygınlık (%)	Yaygınlık (Skala)*	Yoğunluk (adet/m^2)	Yoğunluk (Skala)*
Amaranthaceae	*Amaranthus retroflexus* L.	Kırmızı köklü tilki kuyruğu	35	Y	1,25	C
	Chenopodium botrys L.	Yapışkan kazayağı	20	O	0,85	D
	Chenopodium album L.	Sirken	45	Y	1,75	C
Asteraceae	*Lactuca virosa* L.	Acı marul	5	N	0,35	D
	Lactuca serriola L.	Dikenli yabani marul	25	Y	1,35	C
	Taraxacum serotinum (Waldst and Kit.) Poir	Karahindiba	5	N	0,3	E
	Xanthium strumarium L.	Domuz pıtrağı	40	Y	1,6	C
	Conyza canadensis L.	Şifa otu	100	Ç	10,4	A
	Centaurea cyanus L.	Mavi Peygamber çiçeği	15	O	0,65	D
	Anthemis arvensis L.	Tarla köpek papatyası	25	Y	0,95	D
	Silybum marianum (L.) Gaertner	Deve dikeni	15	O	0,35	D
	Cichorium endivia L.	Mavi hindiba	45	Y	0,75	D
	Cichorium intybus L.	Yabani hindiba	10	N	0,05	E
	Senecio vulgaris L.	Kanarya otu	10	N	0,25	D
	Calendula arvensis (Vill) L.	Portakal nergisi	15	O	0,3	D
	Sonchus asper (L.) Hill.	Eşek marulu	100	Ç	2,25	C
Apiaceae	*Bifora radians* Bieb.	Kokarot	10	N	0,1	D
Brassicaceae	*Capsella bursa-pastoris* (L.) Medik.	Çoban çantası	100	Ç	1,6	C
	Cardaria draba (L.) Desv.	Kır teresi	30	Y	0,55	D
	Sinapis arvensis L.	Yabani hardal	100	Ç	10,1	A
	Lepidium draba L.	Diğnik	55	Ç	1,65	C
Boraginaceae	*Heliotropium europaeum* L.	Bambul otu	100	Ç	10,7	A
Cyperaceae	*Cyperus rotundus* L.	Topalak	25	Y	0,7	D
Convolvulaceae	*Convolvulus arvensis* L.	Tarla sarmaşığı	100	Ç	10,6	A
Equisetaceae	*Equisetum arvense* L.	Tarla atkuyruğu	50	Ç	2,65	C
Euphorbiaceae	*Euphorbia chameasyce* L.	Şebrem	15	O	0,6	D
	Euphorbia rigida L.	Sütleğen	30	Y	1,15	C
Fabaceae	Trifolium repens(L). var.repens	Ak üçgül	50	Ç	1,9	C
	Medicago sativa L.	Yonca	40	Y	2,05	C
	Vicia sativa L.	Adi fiğ	25	Y	0,85	D
	Alhagi pseudalhagi (Bieb.) Desv.	Deve dikeni	5	N	0,1	E
	Melilotus officinalis (L.) Desr.	Kokulu sarıyonca	5	N	0,2	E
	Trifolium pratense L.	Çayır üçgülü	100	Ç	10,1	A
Lamiaceae	*Mentha longifolia* (L.) Huds.	Su nanesi	30	Y	1,05	C
Malvaceae	*Malva neglecta* Wallr.	Ebegümeci	100	Ç	2,05	C
	Malva sylvestris L.	Büyük ebegümeci	20	O	0,75	D
Papaveraceae	*Papaver rhoeas* L.	Gelincik	40	Y	1,7	C
	Fumaria officinalis L.	Şahtere	10	N	0,25	E
Plantaginaceae	*Plantago major* L.	İri yapraklı sinir otu	85	Y	3,05	C
	Plantago lanceolata L.	Dar yapraklı sinir otu	100	Ç	3,1	C
	Plantago minor L.	Küçük yapraklı sinir otu	30	Ç	1,95	C
Poaceae	*Cynodon dactylon* (L.) Pers.	Köpek dişi ayrığı	100	Ç	11,4	A
	Elymus repens (L.) Gould.	Ayrık	80	Ç	3,1	C
	Hordeum murinum L.	Duvar arpası	70	Ç	2,1	C
	Poa pratensis L.	Çayır salkım otu	60	Ç	2,9	C
	Setaria verticillata (L.) P.B	Yapışkan ot	100	Ç	10,9	A
	Sorghum halepense (L.) Pers	Kanyaş	40	Y	3,05	C
	Aegilops cylindria Host.	Sakal otu	10	N	0,45	D
	Bromus tectorum L.	Püsküllü çayır	30	Y	1,05	C
	Lolium perenne L.	İngiliz çimi	80	Ç	3,6	C
	Poa annua L.	Salkım otu	40	Y	1,6	C
	Echinochloa crus-galli (L.) P.Baeuv.	Darıcan	50	Ç	3,15	C
Polygonaceae	*Polygonum aviculare* L.	Çoban değneği	100	Ç	10,3	A
	Polygonum convolvulus L.	Sarmaşık çoban değneği	30	Y	0,95	D
	Rumex acetosella L.	Labada	40	Y	1,75	C
	Rumex crispus L.	Kıvırcık labada	90	Ç	3,55	C
Portulacaceae	*Portulaca oleracea* L.	Semiz otu	100	Ç	13,5	A
Primulaceae	*Anagalis foemina* Miller.	Mavi çiçekli farekulağı	80	Ç	3,5	C
Ranunculaceae	*Adonis aestivalis* L.	Kan damlası	20	O	0,75	D
Primulaceae	*Anagalis foemina* Miller.	Mavi çiçekli farekulağı	80	Ç	3,5	C
Ranunculaceae	*Adonis aestivalis* L.	Kan damlası	20	O	0,75	D
	Ranunculus arvensis L.	Tarla düğün çiçeği	20	O	1,3	C
Solanaceae	*Solanum nigrum* L	İt üzümü	30	Y	1,5	C
Scrophulariaceae	*Veronica hederifolia* L.	Adi yavşan otu	20	O	1,75	C
Urticaceae	*Urtica dioica* L.	Isırgan otu	30	Y	1,85	C
Zygophyllaceae	*Tribulus terrestris* L.	Demir dikeni	100	Ç	2,4	C

Bu türlerin ekolojik üstünlükleri, hızlı büyüme yeteneği, yüksek tohum üretim kapasitesi ve geniş çevresel tolerans aralığı ile ilişkilendirilmektedir (Odum, 1971). Bu özellikler, yabancı ot türlerinin farklı habitat koşullarına yüksek uyum kapasitesi göstermesine ve kültür bitkileriyle su, besin ve ışık gibi temel kaynaklar üzerindeki rekabette belirgin bir üstünlük elde etmelerine olanak sağlamaktadır (Yıldırım ve Ekin, 2003; Sardana, 2017). Dolayısıyla, bu türlerin fidanlık üretim alanlarında yoğun biçimde bulunması, hem üretim verimliliğini olumsuz etkilemekte hem de etkin bir yabancı ot yönetimi gereksinimini ortaya koymaktadır (De Mol ve ark., 2015; Küçük, 2019; Küçük ve ark., 2022;).

Monokotiledon ve dikotiledon türlerin karşılaştırılması sonucunda, dikotiledon türlerin hem sayısal üstünlüğe hem de yayılım alanı genişliğine sahip olduğu belirlenmiştir. Bu durum, dikotiledon yabancı otların saksı üretim ortamında ışık ve besin maddeleri rekabetinde avantajlı konumda olduğunu göstermektedir (Tepe, 1989; Uludağ, 1993). Ayrıca, rizom oluşturan ve hızlı çimlenme özelliğine sahip bazı türler, alanda hızla yayılarak yetiştirilen bitkilerin kök gelişimini olumsuz etkilemektedir (Froud-Williams, 1981). Bu bulgular, fidanlık alanlarında yabancı ot yoğunluğunun bitki gelişimi üzerindeki olumsuz etkilerini ortaya koyan diğer çalışmalarla da paralellik göstermektedir (De Mol ve ark., 2015; Küçük, 2019; Küçük ve ark., 2020; Küçük ve ark., 2022).

Tablo 3. Fidanlıklarda yetiştirilen iç ve dış mekân süs bitkilerinde baskın yabancı otlar

Familyası	Latincesi	Türkçe	Yaygınlık (%)	Yaygınlık (Skala)*	Yoğunluk (adet/m^2)	Yoğunluk (Skala)*
Asteraceae	*Conyza canadensis* L.	Şifa otu	100	Ç	10,4	A
Brassicaceae	*Sinapis arvensis* L.	Yabani hardal	100	Ç	10,1	A
Boraginaceae	*Heliotropium europaeum* L.	Bozot, bambul otu	100	Ç	10,7	A
Convolvulaceae	*Convolvulus arvensis* L.	Tarla sarmaşığı	100	Ç	10,6	A
Fabaceae	*Trifolium pratense* L.	Çayır üçgülü	100	Ç	10,1	A
Poaceae	*Cynodon dactylon* (L.) Pers.	Köpek dişi ayrığı	100	Ç	11,4	A
	Setaria verticillata (L.) P. Beauv.	Yapışkan ot	100	Ç	10,9	A
Polygonaceae	*Polygonum aviculare* L.	Çoban değneği	100	Ç	10,3	A
Portulacaceae	*Portulaca oleracea* L.	Semiz otu	100	Ç	13,5	A

Fidanlık üretim alanında yürütülen çalışma sonucunda, baskın türlerin %100 yaygınlık oranına sahip olduğu ve "çok yaygın (A)" kategorisinde değerlendirildiği belirlenmiştir. Türlerin yoğunluk değerleri 10,1–13,5 adet/saksı arasında değişmiş, en yüksek yoğunluk *Portulaca oleracea* L. (13,5 adet/m^2) türünde, ikinci sırada ise *Cynodon dactylon* (L.) Pers. (11,4 adet/saksı) türünde tespit edilmiştir (Tablo 3). Bu durumu sırasıyla *Sinapis arvensis* L., *Heliotropium europaeum* L. ve *Conyza canadensis* L., *Trifolium pratense* L., *Convolvulus arvensis* L., *Setaria verticillata* (L.) P. Beauv. türlerinin de yüksek yoğunluk değerleriyle çalışma alanında önemli bir yer tuttuğu belirlenmiştir. Bu durum, söz konusu türlerin fidanlık ekosisteminde kullanılan yetiştirme materyali ve bakım uygulamalarına farklı düzeylerde tepki verdiğini göstermektedir. Elde edilen bulgular, fidanlık alanlarında uygulanacak yabancı ot yönetim stratejilerinin özellikle baskın ve yüksek rekabet gücüne sahip türler üzerinde yoğunlaştırılması gerektiğini göstermektedir (Uludağ, 1993; Özer ve ark., 2001; Küçük, 2020).

4. Sonuç

Bu çalışma sonucunda, fidanlık üretim alanında tespit edilen baskın yabancı ot türlerinin %100 yaygınlık gösterdiği ve yüksek yoğunluk değerlerine sahip olduğu

belirlenmiştir. Öne çıkan türler arasında *Portulaca oleracea* L**.** (13,5 adet/m^2) ve *Cynodon dactylon* (L.) Pers. (11,4 adet/m^2) yer almakta olup, bu türlerin süs bitkileri üzerinde güçlü bir rekabet baskısı oluşturduğu saptanmıştır. Diğer baskın türler ise *Setaria verticillata* (L.) P. Beauv**.** (10,9 adet/m^2), *Heliotropium europaeum* L. (10,7 adet/m^2), *Convolvulus arvensis* L. (10,6 adet/m^2), *Conyza canadensis* L**.** (10,4 adet/m^2), *Polygonum aviculare* L. (10,3 adet/m^2), *Sinapis arvensis* L. (10,1 adet/m^2) ve *Trifolium pratense* L. (10,1 adet/m^2) olarak belirlenmiştir. Bu sonuçlar, söz konusu türlerin fidanlık ekosisteminde sahip oldukları yüksek yaygınlık ve yoğunluk nedeniyle kontrol çalışmalarında öncelikli hedefler olarak ele alınması gerektiğini açıkça ortaya koymaktadır.

Bu bulgular doğrultusunda, fidanlık üretim alanında uygulanacak yabancı ot yönetim stratejilerinin, özellikle yoğunluk ve yaygınlığı yüksek türlere odaklanacak şekilde planlanması gerekmektedir. Entegre mücadele yaklaşımı kapsamında kültürel, mekanik ve kimyasal yöntemlerin bir arada ve uyumlu biçimde kullanılması önem taşımaktadır. Ayrıca, herbisit kullanımını da içeren ekonomik açıdan uygulanabilir ve pratik tüm yabancı ot kontrol yöntemlerinin etkinliği üzerine detaylı çalışmalar yürütülmeli; elde edilen başarılı bulgular üreticilere ulaştırılarak yaygınlaştırılmalıdır (Küçük ve ark., 2022). Buna ek olarak, düzenli saha sürveylerinin yürütülmesi, yabancı otların yeniden yayılımını sınırlandırarak sürdürülebilir ve çevre dostu bir fidanlık üretim sisteminin oluşturulmasına önemli katkı sağlayacaktır.

Elde edilen tüm bu sonuçlar, fidanlık üretiminde yabancı ot kontrolünün yalnızca mevcut yoğunluk düzeylerine değil, aynı zamanda yaygınlık seviyelerine de odaklanan planlı, bütüncül ve sürdürülebilir bir yönetim yaklaşımını zorunlu kıldığını göstermektedir (Odum, 1971; Benvenuti, 2004; Küçük ve ark., 2022). Böyle bir yaklaşım, baskın türlerin etkin biçimde kontrol edilmesini sağlayarak kaynakların daha verimli kullanılmasına olanak tanırken, uzun vadede fidanlık üretiminde hem ekolojik dengeyi hem de ekonomik sürdürülebilirliği güçlendirilmesine katkı sağlamaktadır.

Çıkar Çatışması

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Modern Methods of Cleaning, Desalination and Conservation of Porous Building Materials in the Restoration of Architectural Heritage

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Abstract

This review article examines modern methods of cleaning, desalination, and conservation of porous building materials (brick, limestone, sandstone, plaster) used in the restoration of architectural heritage from the 18th-20th centuries. The physico-chemical mechanisms of salt corrosion, capillary moisture rise, and biodegradation are analyzed. Traditional (mechanical, poultice-based) and innovative (electrokinetic, laser, biocidal) technologies are systematized with an assessment of their efficiency, depth of action, and long-term performance. Using the example of the Mausoleum of Khoja Ahmed Yasawi (14th century, UNESCO), the implementation of an integrated approach is demonstrated: electrokinetic desalination (removal of 78% of salts), zeolite poultices, laser glaze ablation, and silane hydrophobization, which together ensured the stabilization of the monument while preserving its authenticity. The article also outlines prospects for further development, including digital monitoring, nanomodified materials, and self-regulating protective coatings.

Review Article

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Biocidal Cleaning,

1. Introduction

The problem of preserving architectural heritage, particularly structures from the 18th-20th centuries, has become increasingly relevant in recent decades. Intensive anthropogenic impacts, changing climatic conditions, and insufficiently systematic restoration practices have led to the accelerated deterioration of mineral building materials such as brick, limestone, sandstone, plasters, and concrete surfaces. One of the most damaging and widespread degradation processes is salt-induced corrosion, manifested through efflorescence, scaling, cracking, and loss of mechanical strength (Charola, 2000).

In historic cities of Russia, Europe, and East Asia, this issue is further exacerbated by the absence of drainage systems, rising groundwater levels, and the use of highly alkaline cement materials (Mikhaylova et al., 2018). Salt formation and capillary moisture rise contribute to the accumulation of chlorides, sulfates, and nitrates within the pore structure of materials, causing cyclic volume changes during salt crystallization and consequently weakening the masonry.

Modern approaches to the conservation of cultural heritage require a comprehensive understanding of the physico-chemical mechanisms of degradation, the implementation of effective cleaning, desalination, and conservation techniques, as well as the development of durable repair materials resistant to aggressive environments (RILEM, 2020; European Commission, 2021).

The aim of this review article is to systematize existing and emerging methods of cleaning and desalinating porous building materials used in restoration, and to evaluate their effectiveness, applicability, and future potential based on international practice. Special attention is given to the current condition of the Mausoleum of Khoja Ahmed Yasawi (Kazakhstan, Turkistan) an outstanding example of Timurid architecture of the 14th century and a UNESCO World Heritage Site.

2. Literature Review and Theoretical Background

Issues related to salt contamination and methods for combating efflorescence have been thoroughly examined in both domestic and international studies. Research by Kizilova A. S. and Volkov A.A. demonstrated that the key factors contributing to efflorescence on brick façades include capillary moisture rise from groundwater, compromised foundation waterproofing, the use of mortars with high alkali content, and insufficient ventilation of underground spaces (Kizilova et al., 2023). Chemical analysis of samples revealed the predominance of Na^+, K^+, and SO_4^{2-} ions, confirming the involvement of alkali metals and sulfates in the formation of low-solubility compounds on the surface.

Kononova O.V. and Zhukova M.V. (Kononova et al., 2016) identified several primary causes of efflorescence formation: the use of low-quality brick containing water-soluble salts, migration of portlandite to the surface, and the application of antifreeze additives containing chlorides and nitrates (Patent RF No. 2256627, 2005). To prevent these phenomena, the researchers recommend incorporating barium compounds into brick composition to convert soluble sulfates into insoluble forms, as well as applying silicone-based hydrophobic coatings to the masonry.

From the perspective of restoration technologies, particular interest is presented by the works of Orlenko N. and Li Shuan, which describe Ukrainian experience in applying modern methods of foundation strengthening and cleaning of stone surfaces (Orlenko et al., 2016). The authors specifically highlight the effectiveness of bored injection piles for stabilizing foundations and minimizing deformations of historic buildings. This approach has been widely adopted in restoration projects of Art Nouveau and Neoclassical structures in China.

In both domestic and European practice, electrochemical desalination techniques for porous materials based on the electromigration of salt ions under an applied electric field are being actively investigated (Rörig-Dalgaard, 2009; Paz-García et al., 2020; Ottosen et al., 2021). These methods enable deep removal of chlorides and sulfates from stone and brick surfaces without mechanical intervention (Fig. 1, 2). However, they require strict control of moisture content and pH, as excessive electrolytic activity may lead to leaching of binding components (Rörig-Dalgaard, 2009).

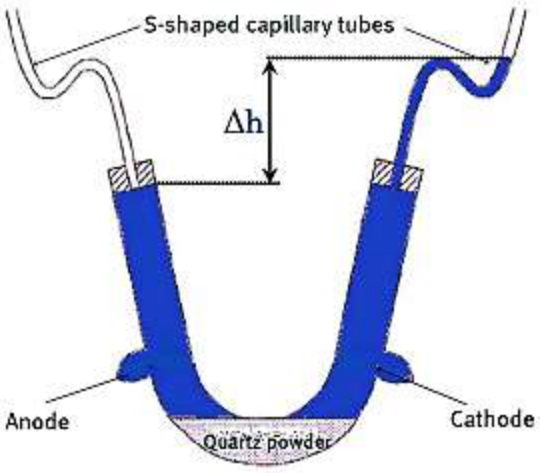

Figure. 1. Reuss classical experiment on electro-osmosis after Abramson (Rörig-Dalgaard, 2009)

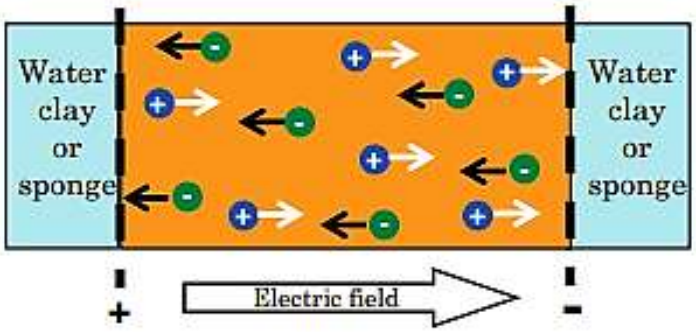

Figure 2. Schematic representation of an electromigration setup (Rörig-Dalgaard, 2009)

A significant contribution to the study of the physico-chemical foundations of the problem has been made by works focusing on the modelling of diffusion processes and capillary moisture transport (Valach et al., 2018; Gilev et al., 2019; Zhang et al., 2021). Based on the Nernst–Planck and Darcy equations, these studies describe the regularities of salt and water migration within porous structures, enabling the prediction of crystallization zones and the selection of optimal drying and cleaning methods.

In international practice, special attention is given to non-destructive diagnostic techniques, including nuclear magnetic resonance (NMR), infrared spectroscopy, and high-resolution microscopy. These methods make it possible to assess the depth of contamination, moisture distribution, and micropore condition without sampling, which is particularly important for unique architectural monuments.

Biochemical cleaning methods are also being actively developed. Research conducted in Russia and Italy has demonstrated the effectiveness of mild biocides based on quaternary ammonium compounds and ethanol mixtures for the removal of microbiological growth, mosses, and mold (Gorbushina, 2007; Cappitelli et al., 2008; Zanardini et al., 2021). In particular, the products Preventol RI80® and Biotin R® have shown high efficiency with minimal color alteration of the stone (BASF, 2022).

As an example of the practical application of desalination and conservation methods, the Mausoleum of Khoja Ahmed Yasawi may be considered the largest architectural structure of the Timurid era in Central Asia, constructed between 1395 and 1405 by order of Tamerlane. The monument is built of fired brick using a lime-gypsum mortar and clad with glazed ceramic tiles. Over six centuries of use, the mausoleum has been subjected to intense salt corrosion caused by capillary rise of groundwater (2.5-3.5 m), high soil mineralization (sulfate content up to 1.8%, chloride content up to 0.6%), and climatic factors (temperature fluctuations from –25 °C to +45 °C; relative humidity 30-70%). Diagnostics carried out from 2018 to 2023 (UNESCO/ICOMOS, Kazakh Research Institute of Restoration) revealed: efflorescence on 65% of the brick surface with a depth of up to 8 cm; microcracks 3-5 mm deep; glaze detachment on 12% of the portal; and biocolonization (Cladosporium spp., Aspergillus niger) on shaded façades. The concentration of water-soluble salts in brick pores reaches 2.4% by mass, which is 5-6 times above the critical threshold (0.4%) (RILEM TC 271-ASC, 2020).

Since 2021, a comprehensive restoration program has been implemented, including electrokinetic desalination (removal of 72% of chlorides within 3 weeks at 1.2 mA/cm^2), multi-cycle zeolite poultices (68% reduction in sulfates), and silane hydrophobization (84% reduction in water absorption). Monitoring in 2024-2025 confirms stabilization of moisture content at 8-12% and the absence of new efflorescence.

Japanese studies also confirm the high efficiency of electrochemical desalination of brick structures. In work by Fukami and Matsui (2022), accelerated laboratory tests were conducted on bricks simulating historical materials from the late 19^{th} century (Fukami et al., 2022). The authors developed a low-cost electrode system based on powdered cellulose (Arbocel BC1000) as a moisture carrier and copper plates as electrodes. It was shown that at a voltage of 5 V and current of 0.5-1 A, it is possible to remove 64-73% of sulfate ions from samples containing Na_2SO_4, which is comparable to the performance of European electrokinetic systems. An important conclusion of the study is the feasibility of localized treatment: only masonry fragments showing efflorescence are desalinated, significantly reducing the cost of conservation for cultural heritage objects under limited municipal budgets. The authors emphasize that this method is particularly promising for regions with heterogeneous brick surfaces and sporadic manifestations of salt corrosion.

Thus, the available literature covers a wide spectrum of approaches from traditional mechanical and chemical methods to innovative electrochemical and biotechnological solutions (RILEM TC 271-ASC, 2020). However, issues remain regarding the compatibility of different methods, the long-term durability of their effects, and their influence on material microstructure, all of which require systematic analysis and comparative evaluation.

3. Physico-Chemical Mechanisms of Degradation of Porous Building Materials

The study of degradation processes in porous materials such as brick, limestone, sandstone, and plaster is of fundamental importance for selecting appropriate restoration methods. The main mechanisms of deterioration include capillary moisture rise, salt crystallization within pores, freeze-thaw cycles, as well as the impact of acid deposition and biological activity (Grossi et al., 2004; Frolova, 2020).

3.1. Capillary transport of moisture and salts

Capillary uptake of moisture from groundwater and atmospheric precipitation is the primary source of dissolved salts entering the depth of masonry. As shown in the studies by Kizilova and Volkov, capillary rise may reach 1.5-2.0 m depending on pore diameter. Dissolved salts primarily sodium chlorides and potassium sulfates are transported with moisture and crystallize as water evaporates at the surface (Rodriguez-Navarro et al., 1999).

This process is accompanied by significant crystallization pressure, which can reach 20-30 MPa, exceeding the compressive strength of brick and limestone. Repeated dissolution and recrystallization cycles lead to pore enlargement, microcracking, and surface scaling (RILEM TC 271-ASC, 2020).

3.2. Influence of material chemical composition

Mineral binders used in historical masonry contain alkaline impurities (Na_2O, K_2O), which contribute to the formation of soluble salts. In cement mortars, the concentration of alkalis may reach 2.5%, accelerating efflorescence formation (Kizilova et al., 2023). Studies have shown that reducing alkali content and incorporating pozzolanic additives help decrease the amount of water-soluble salts and stabilize material structure (Gilev et al., 2019).

Particular importance is attributed to the carbonation of portlandite ($Ca(OH)_2$), which reacts with atmospheric CO_2 to form calcium carbonate that appears as a whitish surface film on brick (Kononova et al., 2016). Carbonation is accompanied by changes in pH and reduced coating adhesion, further accelerating deterioration.

3.3. Temperature and moisture effects

Repeated freeze-thaw cycles of moisture within material pores generate internal stresses and promote cracking. Salt-saturated solutions crystallize at lower temperatures, intensifying micro-destructive processes. As noted by Orlenko and Li Shuan (Orlenko et al., 2016), rising groundwater levels and uneven foundation freezing are key factors contributing to building instability (Orlov, 2015).

3.4. Biological and atmospheric degradation

Stone and plaster surfaces are prone to colonization by microorganisms (algae, fungi, lichens) that produce organic acids, which contribute to mineral decomposition (Gorbushina, 2007). Moreover, dust deposits and industrial pollutants create an acidic environment that accelerates corrosion of limestone and marble (Grossi et al., 2004).

3.5. Combined effects of degradation factors

In practice, degradation processes rarely occur in isolation. Observations on monuments in Saint Petersburg and Prague show that the combined effects of capillary moisture, atmospheric pollution, and biocolonization lead to complex surface deterioration: chemical corrosion is accompanied by mechanical weathering and loss of decorative layers (Grissom, 2021). In the Mausoleum of Khoja Ahmed Yasawi, the combined impact of capillary rise, salt crystallization, and biocolonization is particularly pronounced. In the lower wall zone (up to 2 m), subflorescence of sodium sulfate (thenardite) is observed, causing volumetric expansion of up to 300%, while on the portal, potassium nitrate efflorescence is exacerbated by wind erosion. Freeze-thaw cycles (up to 45 events per year) lead to brick scaling to a depth of 2-3 mm (Orlov, 2015). Thus, the degradation of porous building materials is caused by a complex interaction of physico-chemical and biological processes, necessitating an integrated approach to the development of cleaning and protection methods (RILEM TC 271-ASC, 2020).

4. Traditional Methods of Cleaning and Desalination

Historically, various methods have been used in restoration practice to remove salt contamination, including mechanical, chemical, and sorption techniques. Their effectiveness and applicability depend on the type of contamination, the composition of the material, and the condition of the surface.

4.1. Mechanical methods

The simplest and most accessible approach is mechanical cleaning of surface deposits and efflorescence using soft brushes, steam cleaning, or water-air jets (Kononova et al., 2016). This method is effective for removing surface crusts but does not eliminate salts located within the pores. Often, efflorescence reappears within several months after such cleaning.

4.2. Washing and leaching of salts

Washing with water or weak solutions of acids (acetic or citric) is used to dissolve salt crystals and bring them to the surface. However, excessive moisture can lead to secondary wetting of the masonry and the inward migration of salts. Therefore, modern approaches recommend combining washing with controlled slow drying and air humidity regulation (RILEM TC 271-ASC, 2020).

4.3. Chemical methods

Chemical cleaning relies on the use of acidic or alkaline solutions capable of dissolving salts and contaminants. To remove carbonate and sulfate efflorescence, solutions of ethylenediaminetetraacetic acid (EDTA), ammonium compounds, and phosphates are commonly used (Gilev et al., 2019). However, such agents require strict control to avoid damaging the material matrix. Of particular interest is Russian Patent No. 2198858, which describes a method of suppressing efflorescence by introducing barium compounds into ceramic materials to convert water-soluble sulfates into insoluble forms (Patent RF No. 2198858, 2002). This approach helps prevent efflorescence formation at the manufacturing stage of building materials.

4.4. Sorption and poultice methods

One of the safest and most widely used desalination techniques is the application of poultices paste-like mixtures based on clays, zeolites, perlite, or cellulose fibers applied to the contaminated surface. The poultice absorbs dissolved salts through capillary and osmotic effects. The use of multi-cycle poultices allows achieving a cleaning depth of up to 2-3 cm, which makes the method effective for porous limestones and brick (López-Arce et al., 2010). Practical applications of poultice-based desalination have been documented in Denmark and Greece (López-Arce et al., 2010), where zeolite powder and sepiolite clay mixed with distilled water were used as the active layer. As a result, the salt concentration in the material decreased by 60-70% after two treatment cycles.

4.5. Limitations of traditional methods

Despite their widespread use, traditional methods have several disadvantages:

- short-term effectiveness (risk of repeated salinization under high humidity),
- low efficiency when salts penetrate deeply into the material,
- risk of secondary wetting and leaching of components.

Moreover, mechanical cleaning may damage weakly cemented surfaces, while acidic treatments can cause discoloration and reduced stone strength.

At the Mausoleum of Khoja Ahmed Yasawi, poultices based on bentonite clay and cellulose were used in the 2000s (14-day cycles, 4-5 repetitions), which reduced salt concentration from 2.4% to 0.9% at a depth of 2 cm. However, repeated salinization occurred three years later due to the absence of foundation waterproofing. For these reasons, modern physico-chemical and electrochemical methods have been developed in recent decades, offering deeper removal of contaminants with minimal impact on the material (RILEM, 2020).

5. Modern Physico-Chemical and Electrochemical Technologies for Cleaning and Desalination

The development of restoration technologies in the 21st century is closely linked to the application of physico-chemical and electrochemical methods, which provide high efficiency in contaminant removal while minimizing impact on the material's microstructure. These methods are especially relevant in the restoration of architectural monuments, where mechanical damage to surfaces is unacceptable (Ottosen et al., 2021).

5.1. Electrokinetic methods

5.1.1. Principle of operation

Electrokinetic desalination is based on the movement of salt ions under the influence of a constant electric field. When electrodes are applied to a damp masonry and a low current is passed, dissolved ions such as Na^+, K^+, Cl^-, and SO_4^{2-} migrate from the anode to the cathode. The salt ions are extracted into an electrolyte or sorption paste applied to the surface (Paz-García et al., 2020). The method was first tested in Scandinavia and Italy in the 1980s-1990s and later developed in Russia, Denmark, and Greece (López-Arce et al., 2010). Studies have shown that at a voltage of 10-30 V and a current of 0.5-2 mA/cm^2, 2-4 weeks of treatment can remove up to 80% of chlorides and 60% of sulfates from bricks or limestone blocks 5 cm thick (Rörig-Dalgaard, 2009).

5.1.2. Process features

Key parameters affecting the efficiency of electromigration include material moisture (optimal 15-25%), pore solution conductivity, and electrolyte pH (Paz-García et al., 2020). Excessive voltage can cause the formation of alkaline zones near the cathode and leaching of binder components, so buffer solutions based on weak acids (acetic or citric acid) are recommended (Rörig-Dalgaard, 2009).

5.1.3. Practical applications

In Denmark and Finland, the electromigration method has been successfully used for the restoration of 18th century frescoes and brick facades, where traditional poultices proved ineffective due to the depth of salt penetration (Rörig-Dalgaard, 2009). Similar results were obtained at Volkova's laboratory (Bauman MSTU), where electrokinetic desalination reduced salt concentrations to 0.2% of the material mass (Kizilova et al., 2023). At the Khoja Ahmed Yasawi Mausoleum since 2021, an electrokinetic method has been implemented (Desal®-Pro system, 15 V, buffer – 0.1 M acetic acid). After 21 days of treating a 12 m^2 area, 1.8 kg of chlorides and 2.3 kg of sulfates were removed; the pore solution pH was stabilized at 7.8-8.2. Laser cleaning (Nd:YAG, 1064 nm, 0.6 J/cm^2) was applied to remove soot and biofilms from the glazed majolica portal (45 m² area), $\Delta E < 1.0$.

5.1.4. Advantages and limitations

Advantages:

- Deep cleaning penetration (up to 3-5 cm)

- No mechanical damage
- Process intensity controlled by current and pH

Limitations:

- Necessity to maintain moisture and electrode contact
- High energy consumption
- Risk of local overheating at high conductivity

In addition to European studies, significant contributions to the development of local electro-desalination models were made by Fukami and Matsui (2022), who showed that using powdered cellulose as a hydrophilic carrier stabilizes electrode moisture and prevents direct contact of metal with the brick surface (Fukami et al., 2022). This approach reduces the risk of mechanical destruction and makes the system suitable not only for professional restorers but also for local museum staff and small municipal organizations. The authors demonstrated that optimal effect is achieved with periodic water addition (20% of brick mass), preventing electrode drying and ensuring stable salt electromigration.

5.2. Laser and ultrasonic cleaning

Modern physical methods such as laser ablation and ultrasonic treatment are used to remove contaminants and biofilms from stone surfaces. Laser radiation (typically 1064 nm wavelength, pulse duration <10 ns) allows selective vaporization of contaminants without damaging the substrate. Studies in Italy and Germany have shown that laser cleaning is effective for removing soot and metal deposits but requires precise control of energy density (0.2-1.0 J/cm^2) to avoid overheating. Ultrasonic cleaning is mainly applied to marble and granite. Cavitation flows generated at 20-40 kHz remove weakly bound particles without damaging the crystal lattice. This method has been successfully used in façade restoration in Vienna and Prague (Orlov, 2015).

5.3. Hydrophobization and chemical protection

After cleaning, an important step is hydrophobization – treating the surface with water-repellent compounds based on silicones, silanes, and fluorinated compounds. As noted by Kononova and Zhukova, silicone impregnations (e.g., based on methylsilsesquioxanes) reduce capillary water absorption by 70-90%, preventing the re-entry of moisture and salts (Kononova et al., 2016). The drawbacks of such treatments include limited service life (5-10 years) and sensitivity to ultraviolet light. Modern developments focus on hybrid coatings with silica nanoparticles that maintain vapor permeability and provide long-term protection.

5.4. Materials for repair and restoration work

The effectiveness of cleaning and desalination depends not only on the method but also on the compatibility of repair mortars. According to research (Frolova, 2020), the use of highly alkaline cement mortars can lead to secondary salinization. Lime or lime-pozzolanic mortars with low Na_2O and K_2O content are preferable. Pore structure and capillary activity of the restoration material play a crucial role. The material should have parameters similar to the original masonry to avoid internal stresses during moisture exchange. Studies (Frolova, 2020; Orlov, 2015) have shown that the optimal range of open porosity is 25-35%.

6. Biological Methods of Cleaning and Conservation

6.1. Biodeterioration as a factor of degradation

Biological contamination of façades is one of the least controlled factors in the deterioration of historic buildings. Colonies of microscopic algae, lichens, and fungi not only worsen the appearance of structures but also secrete organic acids (oxalic, citric) that degrade the carbonate matrix of stone (Gorbushina, 2007; Cappitelli et al., 2008).

Microbiological studies show that Cladosporium, Aspergillus, and Penicillium genera dominate on limestone and sandstone, while cyanobacteria and actinomycetes prevail on granite. At high humidity levels (above 75%), biofilm activity increases exponentially (Gorbushina, 2007).

6.2. Chemical biocides

The most common method of combating biodeterioration is the application of chemical biocidal agents to the surface (BASF, 2022).

In the study by Gorbushina (2007), products such as Preventol RI80®, Biotin R®, and Biotin T®, containing quaternary ammonium compounds (benzalkonium chloride, alkyldimethylbenzylammonium), were examined. These compounds disrupt the cell membranes of microorganisms, ensuring surface sterilization for 6-12 months.

Treatment is performed in two stages:

- Application of the biocide solution using a brush or spray;
- Removal of destroyed biofilm residues with soft brushes or compresses.
- For increased effectiveness, the procedure is repeated after 7-10 days.

6.3. Biocompatible and eco-friendly methods

In recent years, growing attention has been given to eco-friendly cleaning methods using natural enzymes and microbiological cultures that degrade organic contaminants without aggressive impact on the mineral substrate (Zanardini et al., 2021).

For example, in Italy, bacterial preparations based on Pseudomonas stutzeri are used, capable of breaking down protein and lipid contaminants without affecting the limestone matrix (Zanardini et al., 2021). Experiments showed that after 48 hours of exposure, biofilm thickness was reduced by 70%, while surface color change did not exceed $\Delta E = 1.5$ (CIE Lab scale).

6.4. Combined technologies

Optimal results are achieved by combining biocidal and physico-chemical cleaning methods. For instance, preliminary treatment with Biotin R® followed by low-energy laser ablation allows the removal of both organic and inorganic contaminants (Luxevisit, 2016).

Such methods are actively implemented in the restoration of façades in Saint Petersburg, Prague, and Venice. Their advantage lies in minimal changes to surface color and texture while achieving a high degree of sterilization.

6.5. Prospects for development

Current research focuses on developing “smart” biocides with prolonged activity, which are activated by increased humidity or temperature. Coatings containing silver, copper, and zinc nanoparticles are being developed to provide long-lasting antimicrobial effects (Grissom, 2021).

Additionally, work is underway to integrate biodiagnostic methods (fluorescence microscopy, DNA sequencing) into façade monitoring programs, allowing timely detection of microbial colonization and prevention of further deterioration.

At the Khoja Ahmed Yasawi Mausoleum, the biocide Preventol RI80® (0.5% solution) was used in 2022 to treat shaded façades (180 m^2); after 72 hours, the bio-load was reduced by 94%, and no recolonization was recorded over two years (BASF, 2022).

7. Materials for Repair and Conservation of Building Surfaces

Restoration work involving cleaning and desalination is closely linked to the subsequent reconstruction of lost masonry fragments and the protection of surfaces against renewed exposure to moisture and contaminants. The effectiveness of these measures depends on the compatibility of repair materials with the originals and their resistance to moisture, salts, and temperature fluctuations.

7.1. Requirements for repair materials

The main criteria for selecting materials for restoration are:

- Physical compatibility (similar porosity, thermal expansion coefficients, and capillary absorption rates);
- Chemical compatibility (absence of reactions between old and new components);
- Environmental stability (low emission of volatile compounds, absence of toxic additives).

The use of highly alkaline cement mortars can lead to secondary salinization. Therefore, lime and lime-pozzolanic mixtures are preferred, as they have lower water permeability and better vapor permeability (Frolova, 2020).

7.2. Modern composite materials

Modern repair mortars are developed based on modified lime formulations with the addition of micro- and nanosilica, metakaolin, and cellulose fibers. These additives increase compressive strength and resistance to salt corrosion while maintaining high vapor permeability.

The use of microsilica (SiO_2 < 0.1 μm) promotes the formation of additional calcium silicate hydrates (C–S–H), improving adhesion to the substrate and reducing capillary water absorption by 40-50%.

A promising direction is also the development of hydrophobic lime mortars containing silane or fluorinated additives, which form a thin protective layer that prevents water penetration without impairing gas exchange.

7.3. Conservation coatings

After cleaning and restoration, surfaces are often coated with protective film-forming materials that create a barrier against moisture and contaminants. The most common are organosilicon lacquers, wax emulsions, and acrylic dispersions (Luxevisit, 2016).

However, excessively dense coatings can interfere with water vapor diffusion, leading to moisture accumulation beneath the film and accelerating deterioration. Therefore, modern research focuses on developing self-regulating membrane coatings that adjust vapor permeability depending on ambient humidity.

In Russia and Europe, biocompatible impregnations with antiseptic properties, based on natural oils, waxes, and silica, are being actively studied (Luxevisit, 2016). They help reduce contamination and biodeterioration without altering the surface appearance.

8. Comparative Analysis of Cleaning and Desalination Methods

Based on the analysis of the sources presented, the key characteristics of various restoration methods can be identified (Table 1).

Table 1. Comparative characteristics of modern restoration methods

Method	Penetration Depth	Material Preservation	Environ-mental Friendliness	Longe-vity of Effect	Notes
Mechanical Cleaning	Low (≤1 mm)	Medium	High	Low (up to 6 months)	Risk of scratches, potential for recurring efflorescence
Acid Wash	Medium (1-3 mm)	Low	Medium	Medium (1 year)	Possible leaching of calcium
Poultices and Sorption Pastes	High (up to 3 cm)	High	High	Medium (2-3 years)	Safe method, requires multiple cycles
Electrokinetic Desalination	Very high (up to 5 cm)	High	Medium	High (5-10 years)	Energy-intensive process
Laser Cleaning	Surface (≤0.5 mm)	Very high	High	High	Selective action
Biological Methods	Surface	Very high	High	Medium (1-2 years)	Requires repeated application
Hydrophobization	-	High	High	High (5-10 years)	Preventive effect

Analysis shows that electrokinetic and poultice-based methods are the most effective for deep salt removal, whereas laser and biological cleaning ensure precise elimination of surface contaminants (Rörig-Dalgaard, 2009; Zanardini et al., 2021). Optimal results are achieved by combining these technologies, as confirmed by façade restoration practices in Denmark, Italy, Ukraine, and Russia (Rörig-Dalgaard, 2009; Orlenko et al., 2016; Luxevisit, 2016).

The combined approach includes the following stages:

- Diagnosis of the material's moisture and salt condition;
- Electrokinetic or sorption desalination;
- Gentle biological or laser surface cleaning;
- Hydrophobization and application of a protective coating;
- Monitoring of the material's condition over subsequent years.

This approach reduces the risk of secondary salinization, improves the stability of the decorative layer, and ensures long-term conservation without compromising the material's authenticity. Incorporating the Japanese model of local electrokinetic desalination (Fukami and Matsui, 2022) demonstrates that modern low-cost systems can achieve a level of desalination comparable to more expensive European installations (Fig. 3) (Fukami et al., 2022).

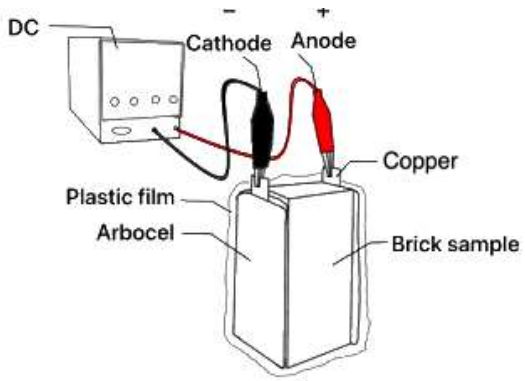

Figure 3. ED model (Fukami et al., 2022)

The method is especially effective for partial treatment of damaged masonry zones and reflects a global trend toward adaptive, energy-efficient, and localized restoration practices.

9. Conclusion

A review of existing and modern methods for cleaning and desalination of porous building materials shows that salt and biological degradation of architectural heritage remains one of the key challenges in contemporary restoration science. Traditional methods, such as mechanical cleaning and acid washes, although simple to apply, have limited effectiveness and may cause secondary damage. Sorption and poultice-based techniques provide deep salt extraction without mechanical impact, but require multiple repetitions. Modern electrokinetic methods enable the removal of salt ions from the interior of materials to depths of several centimeters while preserving their structure. Their application is particularly effective in restoring stone and brick façades, where traditional methods are insufficient. Laser and ultrasonic cleaning represent a new direction in non-destructive technologies, allowing selective contaminant removal while preserving the surface microrelief. Biological and biocompatible methods are a promising eco-friendly solution, allowing control over microbial growth without aggressive reagents. Overall, contemporary restoration practice demonstrates a shift from single-stage interventions to integrated technologies, including diagnosis, physico-chemical cleaning, biocidal treatment, and protective hydrophobization.

To achieve maximum effectiveness, it is necessary to:

- Develop methods for modeling moisture and salt transport to predict recontamination periods;
- Create new buffer and self-regulating materials for electrokinetic cleaning;
- Implement digital monitoring systems for heritage objects (humidity, pH, and conductivity sensors);
- Continue research on eco-friendly and biocompatible compositions for long-term surface protection.

The Khoja Ahmed Yasawi Mausoleum illustrates the effectiveness of a comprehensive approach: diagnosis (NMR, ion chromatography) → electrokinetic desalination + poultices → biocidal treatment → laser cleaning → hydrophobization → monitoring (Testo 635 sensors). Over four years, salt concentration decreased from 2.4% to 0.3%, and the visual integrity of the portal was restored by 98%. The results of Fukami and Matsui (2022) highlight the importance of developing local, cost-effective, and technologically simple electrochemical desalination systems that can be implemented even under conditions of limited skilled personnel and funding. Combining such technologies with traditional poultice methods, biocidal treatments,

and hydrophobization allows the creation of sustainable restoration complexes suitable for monuments in any climatic zone. Thus, the optimal strategy for preserving porous building materials is a combination of scientifically justified physical, chemical, and biological methods, taking into account the microstructure, composition, and climatic conditions of each specific object.

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Termal Yabancı Ot Kontrolü Alanında Yayın Eğilimleri: Bibliyometrik Bir Analiz

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Özet

Yabancı otlar, tarımsal üretimde önemli düzeyde verim ve kalite kayıplarına neden olurken, kentsel alanlarda ekosistem dengesini olumsuz etkileyerek bakım ve yönetim maliyetlerini artırmaktadır. Geleneksel kimyasal yöntemler kısa vadede etkili olsa da, çevre, biyolojik çeşitlilik ve insan sağlığı üzerinde olumsuz etkilere sahiptir. Bu nedenle kimyasal içermeyen ve çevre dostu alternatifler önem kazanmış, özellikle termal yöntemler araştırmaların odak noktası hâline gelmiştir. Bu çalışma, termal yabancı ot kontrolü alanındaki bilimsel yayın eğilimlerini bibliyometrik açıdan incelemektedir. Web of Science veri tabanından elde edilen 1981–2025 dönemi verileriyle 498 bilimsel belge analiz edilmiştir. Bulgular, 2010'lardan itibaren yayın sayılarında belirgin bir artış olduğunu göstermektedir. Atıf analizleri, Fontanelli M., Peruzzi A., Frasconni C. ve Raffaelli M. gibi araştırmacıların yüksek yayın ve atıf sayılarıyla öne çıktığını ortaya koymuştur. Anahtar kelime incelemeleri, çalışmaların temel odaklarının "thermal weed control","weed management","non-chemical weed control","flaming", "temperature" ve "thermal time" olduğunu; araştırmaların başlangıçta tarımsal üretime yoğunlaştığını, ancak zamanla tarım dışı alanlara doğru genişlediğini göstermektedir. Yayınlar öncelikle Weed Research ve Weed Science gibi dergilerde yer almış, ardından tarım, biyoloji ve mühendislik odaklı dergilerde de yayımlanmıştır. Sonuç olarak, termal yabancı ot kontrolü, çevresel sürdürülebilirliği destekleyen ve ekosistem sağlığını koruyan bir strateji olarak, disiplinler arası işbirliği gerektiren, gelecekte bütüncül yabancı ot yönetiminde önemli bir alan olarak öne çıkmaktadır.

Derleme Makalesi

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Anahtar Kelimeler
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Publication Trends in Thermal Weed Control: A Bibliometric Analysis

Abstract

Weeds cause significant yield and quality losses in agricultural production, while negatively impacting ecosystem balance in urban areas and increasing maintenance and management costs. Although traditional chemical methods are effective in the short term, they have negative effects on the environment, biodiversity, and human health. Therefore, chemical-free and environmentally friendly alternatives have gained importance, and thermal methods, in particular, have become the focus of research. This study examines the trends in scientific publications in the field of thermal weed control from a bibliometric perspective. 498 scientific documents were analyzed using data from the Web of Science database covering the period 1981–2025. The findings show a significant increase in the number of publications since the 2010s. Citation analyses revealed that researchers such as Fontanelli M., Peruzzi A., Frasconni C., and Raffaelli M. stand out with high publication and citation numbers. Keyword analyses indicate that the primary focus of the studies is "thermal weed control", "weed management", "non-chemical weed control", "flaming", "temperature", and "thermal time"; research initially focused on agricultural production but expanded to non-agricultural areas over time. Publications primarily appeared in journals such as Weed Research and Weed Science, and subsequently in journals focusing on agriculture, biology, and engineering. Consequently, thermal weed control stands out as a key area in holistic weed management for the future, requiring interdisciplinary collaboration as a strategy that supports environmental sustainability and protects ecosystem health.

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1.Giriş

Yabancı otlar, tarımsal üretimde verimliliği sınırlayan başlıca biyotik faktörler arasında yer almaktadır (Swanton ve Murphy, 1996; Oerke, 2006; Heap, 2014; Chauhan, 2020). Kültür bitkileriyle aynı ekosistemi paylaşan bu bitkiler, su, ışık, besin maddeleri ve yaşam alanı gibi temel kaynaklar üzerinde rekabete girerek ürün veriminde ciddi kayıplara yol açmaktadır. Bunun yanı sıra, ürün kalitesini olumsuz etkileyerek hasat süreçlerini güçleştirmekte ve birçok patojen ile zararlıya konukçuluk ederek dolaylı zararlar meydana getirmektedir (Chauhan, 2012). Yabancı otların neden olduğu verim kayıplarının derecesi ise ekilen bitki türü, iklim koşulları, yabancı ot yoğunluğu ve uygulanan kontrol yöntemlerine bağlı olarak önemli ölçüde değişkenlik göstermektedir Oerke, 2006; Sardana ve ark., 2017; Chauhan, 2020; (Damalas, 2022; Horvath ve ark., 2023). Benzer şekilde, tarım dışı alanlarda da yabancı otlar çeşitli sorunlar ortaya çıkarmaktadır. Özellikle yol kenarları, parklar, kaldırımlar ve rekreasyon alanlarında kontrol altına alınmadığında, estetik kayıplara sebep olmakta, alanın işlevselliğini azaltmakta, kuruyan yabancı otlar yangın riski oluşturmakta ve terk edilmişlik hissi uyandırmaktadır (Tepe, 1997; Jodoin ve ark., 2008; Rask, 2012; Gürbüz ve ark., 2019; Koç, 2019; Koç, 2025). Dolayısıyla yabancı otlarla mücadele yalnızca tarımsal üretim açısından değil, aynı zamanda kentsel ve kamusal alanların sürdürülebilirliği açısından da önemli bir konudur.

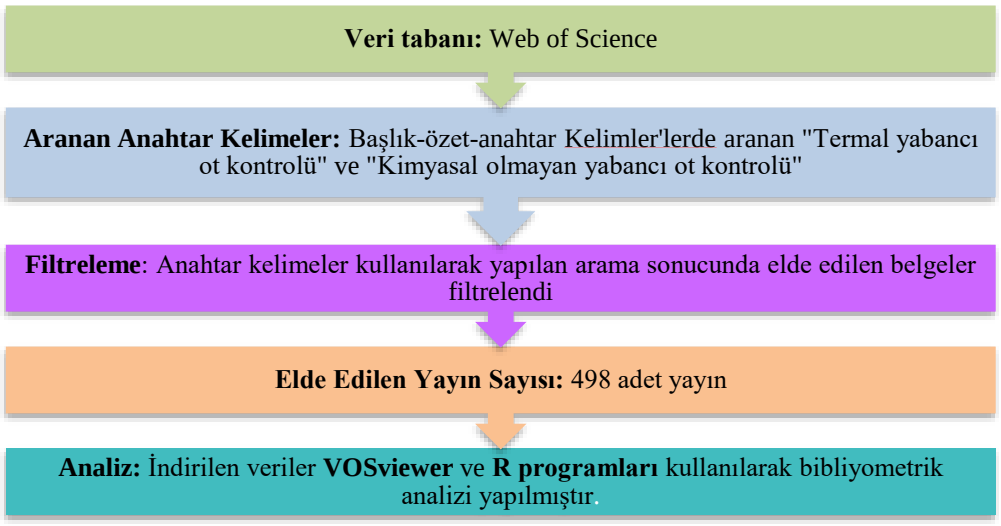
Günümüzde yabancı otların kontrolünde en sık başvurulan yöntemlerden biri kimyasal mücadeledir. Herbisitler, kolay uygulanabilir olmaları ve kısa sürede etkili sonuç vermeleri nedeniyle yaygın biçimde tercih edilmektedir. Ancak aşırı ve bilinçsiz kullanım; çevre kirliliği, toprak ve su kaynaklarında kalıntı birikimi, biyolojik çeşitlilikte azalma ve insan sağlığı üzerinde riskler yaratmaktadır (Aktar ve ark., 2009; Ali ve ark., 2020; Gandhi ve ark., 2021; Beaumelle ve ark., 2023; Ahmad ve ark., 2024). Ayrıca, yoğun herbisit kullanımı sonucunda dayanıklı yabancı ot popülasyonlarının gelişmesi, mevcut sorunları daha da karmaşık hale getirmektedir (Manalil ve ark., 2011; Vencill ve ark., 2012; Shaner, 2014; Heap, 2014; Duke, 2015; Baucom, 2019). Bu nedenle çevre dostu, sürdürülebilir ve alternatif mücadele yöntemlerine duyulan ihtiyaç giderek artmaktadır. Bu alternatif yöntemlerden biri de termal yabancı ot kontrolüdür. Kimyasal madde kullanılmadan yalnızca ısı enerjisine dayalı olarak uygulanan bu yöntem; sıcak su, sıcak hava, buhar, alevleme ve infrared ışınları gibi doğrudan; mikrodalga, elektrik, UV veya lazer gibi dolaylı tekniklerle gerçekleştirilebilmektedir (Ascard, 1995; Rask ve Kristoffersen, 2007; Rask ve ark., 2012; Rask ve ark., 2013; Çolakoğlu ve Kitiş, 2014; Gürbüz ve ark., 2019; Koç, 2019; Bauer ve ark., 2020; Koç, 2025). Termal etki, bitki dokularında hücre zarının bozulmasına, proteinlerin denatürasyonuna ve sonuç olarak bitkinin ölümüne neden olmaktadır (Ellwanger ve ark., 1973; Merfield, 2010). Protein denatürasyonu 45°C civarında başlamakta, 55–70 °C aralığında ise yapraklarda hızlı hücre ölümü gerçekleşmektedir (Ascard, 1997). Türlere bağlı olarak değişmekle birlikte, özellikle yabancı otların erken gelişim dönemlerinde yapılan termal uygulamalar hem daha etkili sonuçlar vermekte hem de enerji kullanımını ve maliyeti azaltmaktadır (Hansson ve Ascard, 2002; Rask ve Kristoffersen, 2007; De Cauwer ve ark., 2015; Koç, 2025). Dar yapraklı ve çok yıllık türlerin kontrolü daha güç olsa da, termal yöntemler kabul edilebilir düzeyde başarı sağlayabilmektedir (Rask, 2012; De Cauwer ve ark., 2015; Koç, 2025).

Son yıllarda yabancı ot bilimi alanındaki araştırmalar, yenilikçi ve sürdürülebilir kontrol yöntemlerine odaklanmaktadır. Bu eğilim, literatürde yayımlanan çalışmalardaki belirgin artışla da desteklenmektedir. Ancak mevcut bilgi birikiminin tematik odakları, coğrafi dağılımı, disiplinler arası iş birlikleri, öne çıkan araştırmacılar ve etkili dergiler gibi yapısal özelliklerini ortaya koymak için bibliyometrik analizler önemli bir araç olarak kullanılmaktadır (Aria ve Cuccurullo, 2017; Donthu ark., 2021; Niknejad ve ark., 2021;

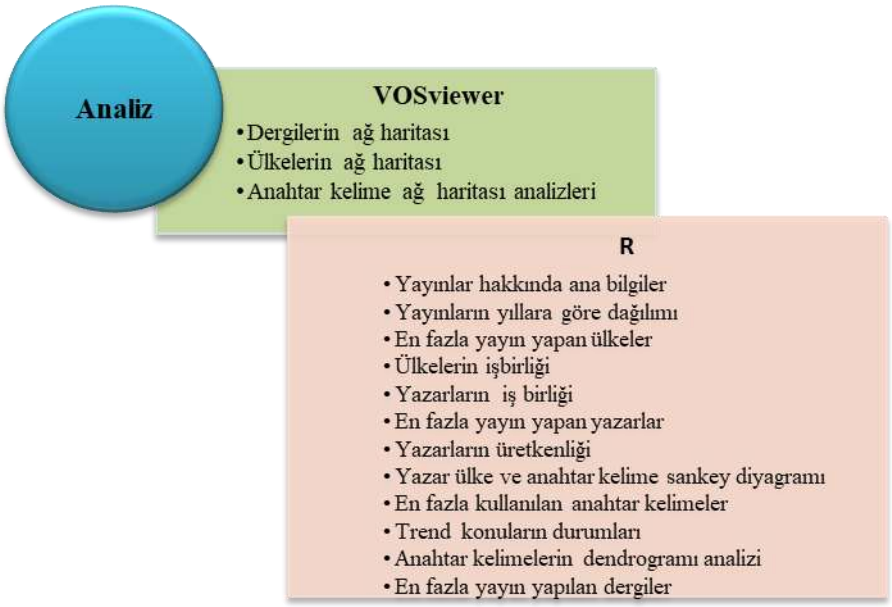
Özbakır, 2023; Koç, 2024). Bibliyometrik yöntemler, özellikle son yıllarda birçok bilim dalında literatürün sistematik haritalanması, mevcut araştırma boşluklarının belirlenmesi ve gelecek çalışmalara yön verilmesi açısından giderek yaygınlaşmaktadır (Zupic ve Čater, 2015; Kulak ve ark., 2019; Mühl ve De Oliveira, 2022; Kulak ve ark., 2025; Koç, 2025). Yabancı ot yönetimi bağlamında bibliyometrik analizler, bilimsel bilginin gelişim sürecini ve araştırma eğilimlerini sistematik bir şekilde ortaya koymakta; özellikle termal yabancı ot kontrolü üzerine yapılan çalışmaların hangi dönemlerde önem kazandığı ve hangi temalarla ilişkili olduğu net bir biçimde izlenebilmektedir. Bu çalışma, yabancı ot bilimi alanında yayımlanmış uluslararası literatürü bibliyometrik yöntemlerle incelemeyi amaçlamaktadır. Analiz kapsamında, yayın eğilimleri, öne çıkan araştırmacılar ve ülkeler, iş birliği ağları ile anahtar kelime temaları belirlenerek, alanın mevcut durumu ve gelecekteki araştırma yönelimleri bilimsel bir çerçevede değerlendirilmektedir. Böylece, yabancı ot yönetiminde termal yöntemlerin literatürdeki konumu ortaya konulmakta ve gelecekteki çalışmalara rehberlik edecek bir perspektif sunulmaktadır.

2. Materyal ve Yöntem

Bu çalışma kapsamında kullanılan materyali, Web of Science veri tabanında "termal yabancı ot kontrolü" ve "kimyasal olmayan yabancı ot kontrolü" anahtar kelimeleri ile gerçekleştirilen taramalar sonucunda elde edilen bilimsel yayınlar oluşturmaktadır. 1981–2025 yıllarını (17.09.2025 tarihine kadar) kapsayan bu tarama sonucunda toplam 498 yayın çalışmaya dâhil edilmiştir. Elde edilen veriler, analizlerde kullanılmak üzere BibTeX formatında dışa aktarılmıştır. Bu araştırmada yöntem olarak, yabancı ot yönetiminde kullanılan termal yöntemlere ilişkin bilimsel yayınların değerlendirilmesi amacıyla bibliyometrik analiz yaklaşımı benimsenmiştir. Bibliyometrik analiz, bilimsel literatürün gelişim dinamiklerini, araştırma eğilimlerini ve bilgi yapısını ortaya koymada yaygın olarak kullanılan bir yöntemdir (Župič ve Čater, 2015; Aria and Cuccurullo, 2017; Donthu ve ark., 2021). Analiz sürecinde iki farklı yazılım aracı kullanılmıştır. Haritalama ve görselleştirme işlemleri VOSviewer yazılımı (Van Eck ve Waltman, 2010) aracılığıyla gerçekleştirilirken, bibliyometrik ağ analizleri Bibliometrix paketi (Aria ve Cuccurullo, 2017) kullanılarak yürütülmüştür. Tüm analizler, R programlama dili temel alınarak RStudio bütünleşik geliştirme ortamı üzerinden gerçekleştirilmiştir. Araştırmada izlenen veri toplama ve analiz sürecine ilişkin akış şeması Şekil 1'de sunulmuş, VOSviewer ve Bibliometrix yazılımları kullanılarak elde edilen analiz çıktıları ise Şekil 2'de gösterilmiştir.



Şekil 1. Bibliyometrik analiz veri akış şeması



Şekil 2. VOSviewer ve R yazılımları ile gerçekleştirilen analizler

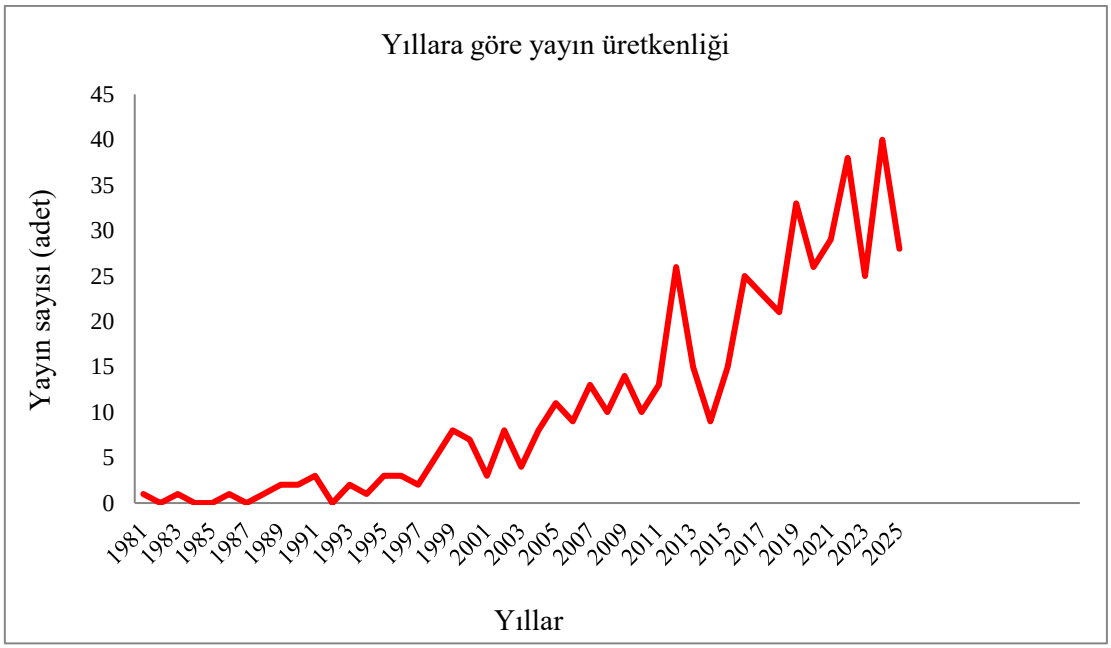
3. Bulgular ve Tartışma

Yabancı otlar, tarım dışı alanlarda önemli ekolojik ve yönetimsel sorunlara neden olmakta, bu durum ise alanların verimli kullanımını kısıtlamakta ve bakım maliyetlerini artırmaktadır (Swanton ve Murphy, 1996; Oerke, 2006; Heap, 2014). Son yıllarda, kimyasal içermeyen ve yenilikçi yöntemler içerisinde özellikle termal yaklaşımlar öne çıkmış; bu bağlamda yabancı ot yönetiminde sürdürülebilir çözümler geliştirilmesine yönelik araştırmaların sayısı artmıştır (Ascard, 1995; Bond ve Grundy, 2001) Bu çalışmada, söz konusu yaklaşımlara ilişkin literatürde yer alan bilimsel yayınların temel özellikleri ve ilgili veriler Tablo 1'de sunulmuştur.

Tablo 1. Yayınlar hakkında ana bilgiler

Veriler hakkında temel bilgiler	**Sonuçlar**
Zaman Aralığı	1981:17.09.2025
Kaynaklar (Dergiler, Kitaplar vb.)	243
Belgeler	498
Yıllık Büyüme Oranı %	7.87
Belge Ortalama Yaşı	10.2
Belge Başına Ortalama Atıf Sayısı	17.27
Anahtar Kelimeleri	1837
Yazarlar	
Yazarlar	1831
Tek Yazarlı Belgelerin Yazarları	17
Tek Yazarlı Belgeler	19
Belge Başına Ortak Yazar Sayısı	4.72
Uluslararası Ortak Yazarlık %	21.49
Belge türleri	
Makale	406
Kitap bölümü	4
Konferans bildirisi	53
Editöryal	1
Derleme makale	34

Yabancı ot kontrolünde termal yöntemlerle ilgili yapılan çalışmalar sonucunda, 1981–17 Eylül 2025 yılları arasında 243 kaynaktan toplam 498 yayın tespit edilmiştir. Belgelerin ortalama yaşı 10.2 yıl olup, her bir yayın ortalama 17.27 atıf almıştır. Yıllık büyüme oranı %7.87 düzeyinde gerçekleşmiştir. Çalışmalara 1.831 yazar katkı sağlamış, makale başına ortalama 4.72 ortak yazar yer almıştır. Uluslararası iş birliği oranı ise %21.49 olup, bu oran araştırma alanında orta düzeyde fakat giderek gelişen bir küresel ağın varlığını göstermektedir. Yayın türleri incelendiğinde, çoğunluğu araştırma makalelerinin (406) oluşturduğu, bunu derleme makalelerinin (34), konferans bildirilerinin (53) ve kitap bölümlerinin (4) izlediği görülmektedir (Tablo 1). Yıllara göre yayın eğilimi ise Şekil 3'te sunulmaktadır.



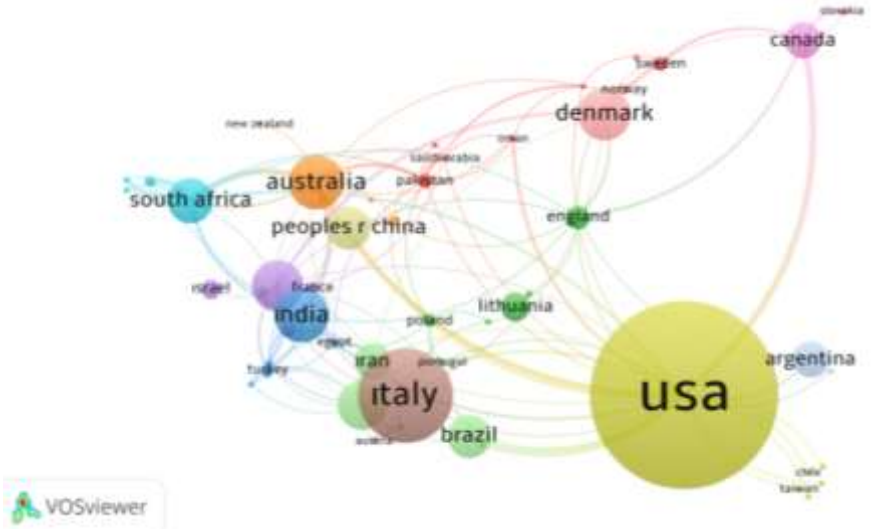
Şekil 3. Yıllara göre yayın üretkenliği

Termal yabancı ot yönetimine ilişkin yıllık bilimsel üretim incelendiğinde, 1981–2000 yılları arasında yayın sayısının oldukça düşük ve durağan bir seyir izlediği görülmektedir. 1996–2005 döneminde ise kısmi bir artış eğilimi gözlenmiş, bazı yıllarda 5–10 yayına ulaşılmıştır. Bu durum, konunun akademik çevrelerde giderek ilgi görmeye başladığını göstermektedir. 2006–2010 yılları arasında yayın sayısında dalgalanmalar olmakla birlikte belirgin bir artışın ortaya çıktığı dikkat çekmektedir. Bu artış, özellikle teknoloji alanındaki ilerlemeler ve çevre bilincinin güçlenmesiyle birlikte termal yöntemlere yönelik araştırmaların hız kazandığını düşündürmektedir. 2011–2025 dönemine gelindiğinde ise bilimsel üretkenlik en yüksek seviyelere ulaşmıştır. Özellikle 2015 sonrası yıllarda yayın sayısında düzenli bir artış eğilimi göze çarpmaktadır. Bu eğilimin arkasında, tarımda kimyasal girdilere alternatif yöntemlerin geliştirilmesine yönelik arayışlar, sürdürülebilir tarım uygulamalarının yaygınlaşması ve çevre dostu teknolojilere artan yönelim gibi faktörlerin etkili olduğu söylenebilir (Chauhan, 2020; Bauer ve ark., 2020; Martelloni ve ark., 2021; Upadhyay ve ark., 2024) (Şekil 3). En fazla yayın yapan ülkeler Tablo 2'de verilmiştir.

Tablo 2. En fazla yayın yapan ülkeler

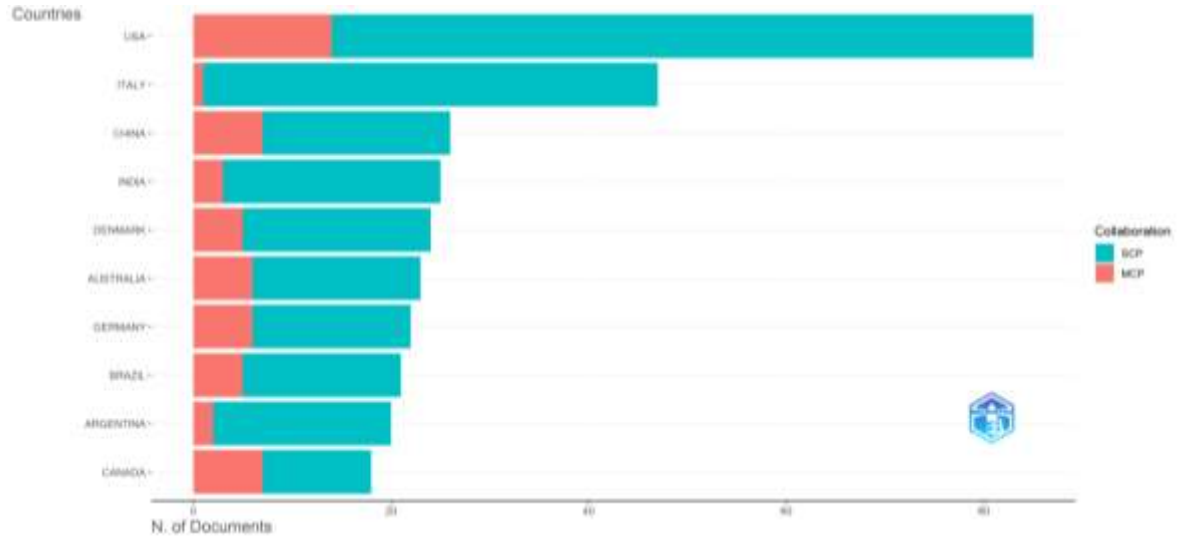
Ülke	Yayın sayısı (adet)
Amerika Birleşik Devletleri	294
İtalya	140
Çin	96
Hindistan	87
İspanya	85
Avustralya	80
Brezilya	80
Güney Afrika	77
Arjantin	70
Danimarka	68
Almanya	66
Kanada	52

Termal yabancı ot yönetimi alanında toplam 68 ülkeye ait yayın tespit edilmiştir. Bu yayınlar arasında en yüksek katkı 294 makale ile Amerika Birleşik Devletleri'ne ait olup, bunu 140 yayın ile İtalya ve 96 yayın ile Çin takip etmektedir (Tablo 2). Ülkeler arasındaki iş birliği ve bağlantılar, Şekil 4'te yer alan ağ haritası ile görselleştirilmiştir.



Şekil 4. Ülkelerin ağ haritası

Ülkeler arası işbirliği ağ haritasında renkler, farklı işbirliği kümelerini temsil etmektedir. Yeşil küme, Amerika Birleşik Devletleri merkez konumda yer almakta ve en geniş uluslararası bağlantı ağına sahip ülke olarak öne çıkmaktadır. Lila küme, İtalya, Danimarka ve Kanada; açık yeşil kümede Çin; mavi kümede Hindistan, Fransa, Güney Afrika, Türkiye ve Arjantin; su yeşili kümede ise Brezilya yer almaktadır. Bu kümeler, farklı bölgeler arasında şekillenen işbirliği yapılarının varlığını ortaya koymakta ve araştırma alanının küresel ölçekte çok merkezli bir yapıya sahip olduğunu göstermektedir. Dolayısıyla, termal yabancı ot kontrolü alanındaki bilimsel üretimin yalnızca belirli ülkelerle sınırlı olmadığı; farklı coğrafyalarda yürütülen çalışmaların, uluslararası bilgi paylaşımını güçlendirdiği ve yenilikçi yöntemlerin küresel ölçekte yaygınlaşmasına önemli katkılar sağladığı anlaşılmaktadır (Şekil 4). Sorumlu yazarların ülkelerine göre yayın dağılımları ve uluslararası işbirlikleri ise Şekil 5'te sunulmuştur.



Şekil 5. Sorumlu yazarların ülkelerine göre yayın dağılımı ve uluslararası işbirlikleri

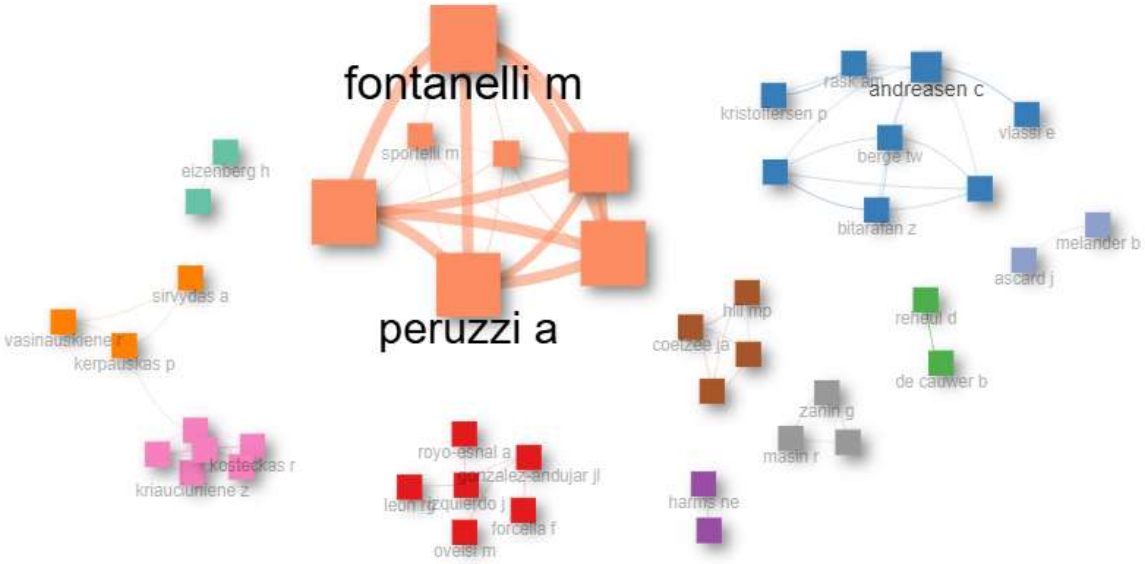
Termal yabancı ot yönetimi alanında en fazla yayın gerçekleştiren ülke Amerika Birleşik Devletleri olup, bu yayınların önemli bir kısmının uluslararası ortak yayınlar (MCP) kapsamında üretildiği görülmektedir. ABD'yi, yüksek yayın sayıları ile İtalya ve Çin takip etmektedir. Özellikle İtalya'da tek ülke kaynaklı yayınların (SCP) öne çıkması dikkat çekmektedir. Hindistan, Danimarka, Avustralya, Brezilya, Arjantin ve Kanada ise uluslararası işbirliklerinde öne çıkan diğer ülkeler arasında yer almaktadır (Şekil 5). Yapılan analiz, en üretken ülkelerin yayın sıklığını ortaya koymakta ve çok ülkeli (MCP) ile tek ülkeli (SCP) yayınların oranlarını karşılaştırmalı olarak göstermektedir. Uluslararası işbirliklerinin, yüksek nitelikli araştırmacıları bir araya getirerek laboratuvarlar arasında bilgi ve deneyim paylaşımını kolaylaştırdığı, böylece araştırma kalitesinin ve bilimsel standartların gelişimine önemli katkılar sağladığı anlaşılmaktadır (Jimoh ve ark., 2022). En fazla yayın üreten yazarların dağılımı ise Tablo 3'te sunulmuştur.

Tablo 3. En fazla yayın yapan yazarlar

Yazar	**h_index**	**AS**	**YS**	**BY**
Fontanelli M.	10	255	19	2011
Frasconıi C.	10	249	18	2011
Peruzzi A.	10	303	18	2011
Raffaelli M.	10	253	18	2011
Martelloni L.	9	211	16	2013
Andreasen C.	8	171	14	1999
Forcella F.	6	542	6	1996
Melander B.	6	476	6	2003
Ascard J.	5	185	5	1994
Coetzee J.A	5	116	7	2007
Gonzalez-Andujar J.L.	5	95	8	2009
Kristoffersen P.	5	139	7	2004
Zanin G.	5	151	6	2006
Bitarafan Z.	4	41	7	2019
Chauhan B.S.	4	176	5	2015
De Cauwer B.	4	48	6	2011

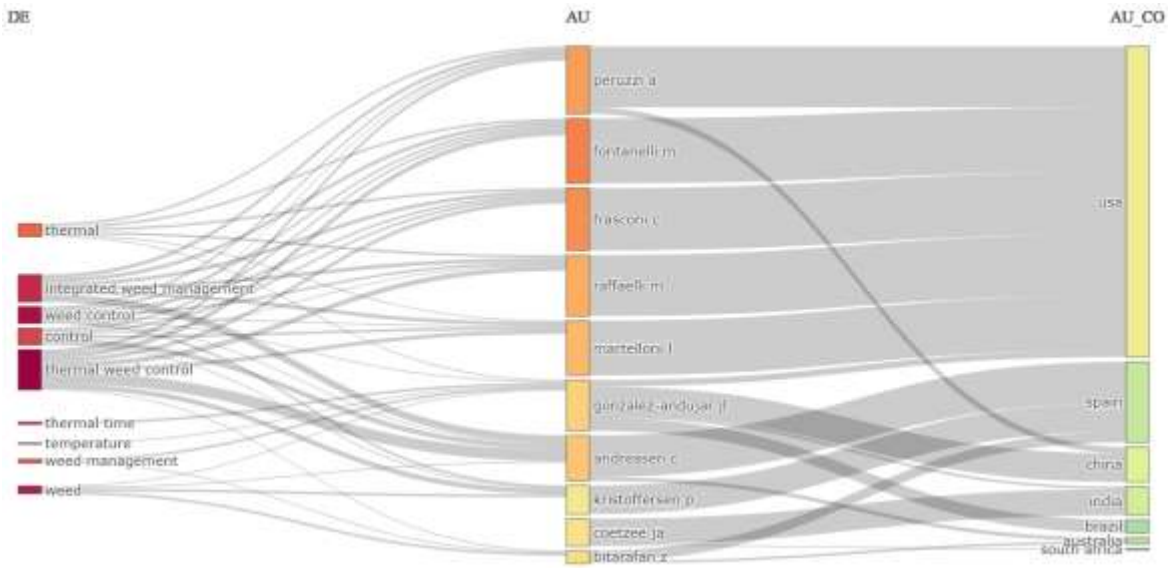
AS; atıf sayısı, YS; yayın sayısı, BY; başlama yılı

Bu alanda en üretken araştırmacı, 2011'den itibaren Fontanelli, M., 19 yayın, 255 atıf ve h-indeks 10 ile alanda en üretken araştırmacı olarak öne çıkmaktadır. Benzer şekilde Frasconni, C. (18 yayın, 249 atıf, h=10), Peruzzi, A. (18 yayın, 303 atıf, h=10) ve Raffaelli, M. (18 yayın, 253 atıf, h=10) de 2011'de alana dahil olmuş ve kısa sürede yüksek etki yaratmıştır. Martelloni, L. ise 2013'ten itibaren yayımladığı 16 çalışma ile 211 atıf ve h-indeks 9 değerine ulaşmıştır. Yüksek etki ancak sınırlı yayın sayısına sahip yazarlar arasında Forcella, F. (6 yayın, 542 atıf, h=6) ve Melander, B. (6 yayın, 476 atıf, h=6) öne çıkmaktadır. Diğer istikrarlı katkı sağlayan isimler Ascard, J. (5 yayın, 185 atıf, h=5), Coetzee ,J.A. (7 yayın, 116 atıf, h=5) ve Kristoffersen P. (7 yayın, 139 atıf, h=5) olup, yeni nesilden Bitarafan Z. (7 yayın, 41 atıf, h=4), Chauhan, B.S. (5 yayın, 176 atıf, h=4) ve De Cauwer, B. (6 yayın, 48 atıf, h=4) son yıllarda yürüttükleri çalışmalar aracılığıyla alan literatürüne kayda değer katkılar sunmaktadır (Tablo 3). Yazarlar arasındaki iş birliği Şekil 6'daki ağ grafiği ile gösterilmiştir.



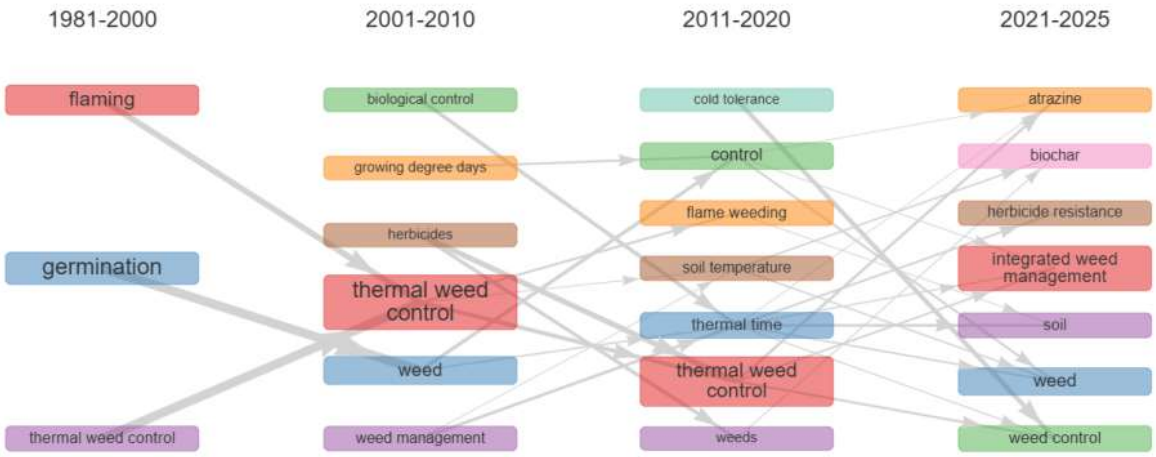
Şekil 6. Yazarların ağ grafiği analizi

Yazar iş birliği ağı incelendiğinde, turuncu küme**,** Fontanelli, M. ve Peruzzi, A. etrafında yoğunlaşmakta ve ağın merkezini oluşturmaktadır. Fontanelli, M. en büyük düğüme sahip olup üretkenlik ve etki açısından öne çıkmaktadır. Mavi küme**,** Andreasen, C. liderliğinde Kristoffersen, P., Rask, E., Berge, T. W. ve Bitarafan, Z. gibi isimlerle güçlü iç bağlantılar sergilemekte, ancak diğer kümelerle ilişkileri sınırlı kalmaktadır. Mor ve kahverengi kümeler, Harms, N. E., Masini, R., Zanin, G., Coetzee, J. A. ve Hill, M. P. gibi araştırmacılar etrafında şekillenmiş küçük ve parçalı yapılardan oluşmaktadır. Yeşil küme ise Renaud, D. ve De Cauwer, B. gibi isimlerin yer aldığı daha sınırlı bağlantılara sahip küçük bir grubu temsil etmektedir. Genel olarak ağ, hem köklü araştırmacılar etrafında gelişen merkezleri hem de son yıllarda alana katılan yeni araştırmacıları barındırarak çok merkezli bir iş birliği yapısı ortaya koymaktadır (Şekil 6). Çalışmalarda yer alan öncü yazarları (AU), bunların ait olduğu ülkeleri (AU_CO) ve ilişkili oldukları anahtar kelimeleri (DE) sankey diyagramı Şekil 7'da verilmiştir.



Şekil 7. Yazar - ülke ve anahtar kelime sankey diyagramı

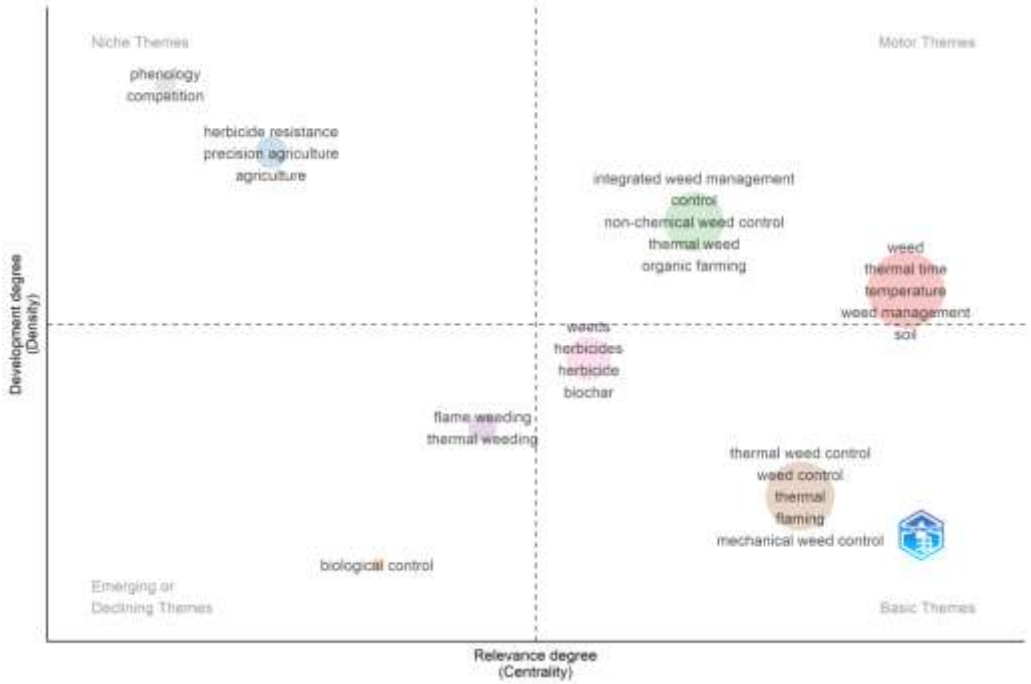
Yazarların uluslararası işbirlikleri ve araştırma odakları incelendiğinde, Fontanelli, M., Peruzzi, A., Frasconi, C., Raffelli, M. ve Martelloni, L. ağırlıklı olarak ABD ile işbirliği yaparken, araştırmalarını ‘’termal yöntemler’’, ‘’entegre yabancı ot yönetimi’’ ve ‘’yabancı ot kontrolü’’ konularına yoğunlaştırmaktadır. İspanya merkezli yazarlar Andreasen, C., Kristoffersen, P., Coetzee, J. A. ve Bitarafan, Z. ‘’yabancı ot yönetimi’’ ve ‘’termal yabancı ot kontrolü’’ temalarına odaklanmaktadır. Çinli Gonzalez-Andujar, J. L. ise ‘’yabancı ot’’, ‘’sıcaklık zamanı’’ ve ‘’sıcaklık’’ konularına öncelik vermektedir. Hindistan, Brezilya, Avustralya ve Güney Afrika’dan yazarlar da ‘’termal yabancı ot kontrolü alanına’’ katkı sağlamaktadır (Şekil 7). Anahtar kelimelerin zaman içindeki evrimi (1981–17 Eylül 2025) Şekil 8’de gösterilmiştir.



Şekil 8. Anahtar kelimelerin zaman içindeki evrimi

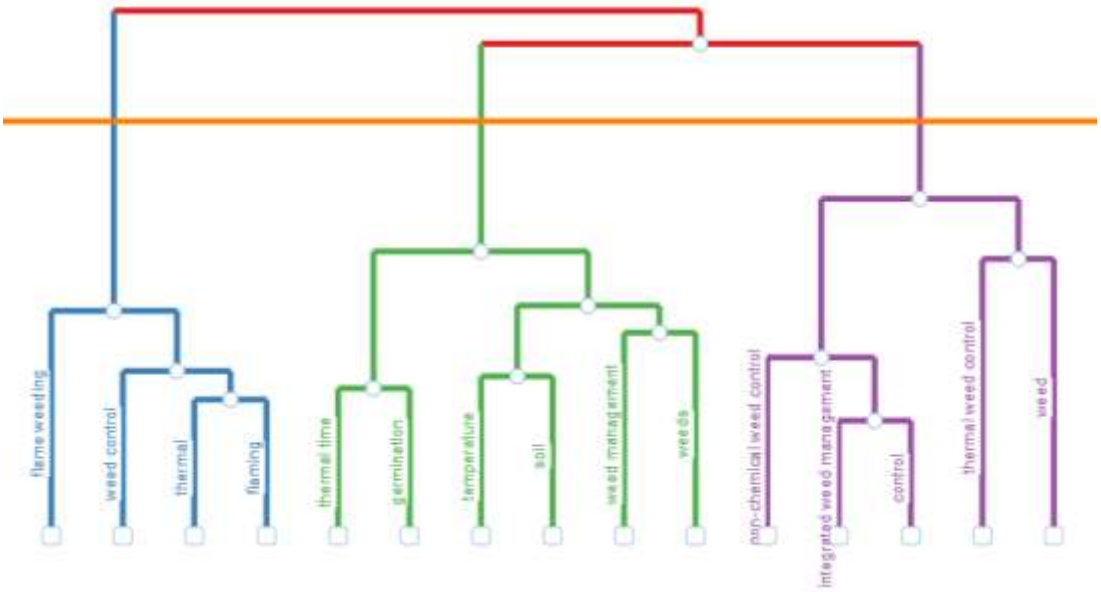
Anahtar kelimelerin zaman içindeki değişimi incelendiğinde, yabancı ot bilimi araştırmalarının evrimi açıkça görülmektedir. 1981–2000 yılları arasında, temel konulara odaklanılmıştır; bu dönemde "flaming",germination ve thermal weed control" gibi kavramlar ön plana çıkmıştır. 2001–2010 yıllarında ise, "biological control, growing degree days, herbicides, thermal weed control, weed ve weed management" gibi daha kapsamlı ve entegre yaklaşımlar araştırılmıştır. 2011–2020 döneminde, "cold tolerance, control, flame weeding, soil temperature, thermal time, thermal weed control ve weeds" gibi konulara odaklanılmıştır.

En güncel dönem olan 2021–2025 aralığında ise, çalışmaların yönü "atrazine, biochar, herbicide resistance, integrated weed management, soil, weed ve weed control" gibi sürdürülebilirlik temelli kavramlara kaymıştır. Bu eğilim, yabancı ot bilimi araştırmalarının klasik kontrol yöntemlerinden dijital teknolojiler, sürdürülebilirlik ve yenilik odaklı modern yaklaşımlara doğru evrildiğini göstermektedir (Şekil 8). Tematik harita analizi Şekil 9'da verilmiştir.



Şekil 9. Tematik harita analizi

Tematik harita analizi, yabancı ot bilimi alanındaki araştırmaların temel yapı taşlarını ve dinamiklerini ortaya koymaktadır. Motor Temalar (sağ üst) arasında ''integrated weed management'',control,non-chemical weed control, thermal weed, organic farming, weed, thermal time, temperature, weed management, soil bulunmakta olup, bu kavramlar hem yüksek merkeziliğe hem de güçlü gelişim düzeyine sahip olup alanın araştırma dinamiklerini yönlendiren ana konuları temsil etmektedir. Niche Temalar (sol üst) kategorisinde yer alan kavramlar, yabancı ot bilimi alanında belirli alt disiplinlerde önemli olsa da, genel araştırma dinamiklerine sınırlı katkı sağlamaktadır. Bu temalar arasında phenology, competition, herbicide resistance, precision agriculture, agriculture'' yer almaktadır. Emerging or Declining Temalar (sol alt) bölümünde yer alan ''flame weeding, thermal weeding ve biological control'' yöntemler geçmişteki etkinliklerine rağmen, günümüzde daha verimli ve sürdürülebilir alternatiflerin gelişmesiyle birlikte daha az tercih edilmektedir.Temel/Çapraz Temalar (sağ alt) arasında yer alan ''weeds, herbicides, herbicide, biochar, thermal weed control, weed control, thermal, flaming ve mechanical weed control'' kavramları yüksek merkezilikleriyle yabancı ot bilimi alanının temel yapı taşlarını oluşturmaktadır. Termal yabancı ot yönetimine yönelik araştırmalar, kimyasal olmayan yabancı ot yönetimi ve termal yöntemlerin disiplinler arası bir merkezi rol oynadığını göstermektedir. Bu eğilim, alanın daha çevre dostu ve verimli yönetim stratejilerine yöneldiğini göstermektedir (Şekil 9). Anahtar kelimelerin dendrogramı Şekil 10'te sunulmuştur.

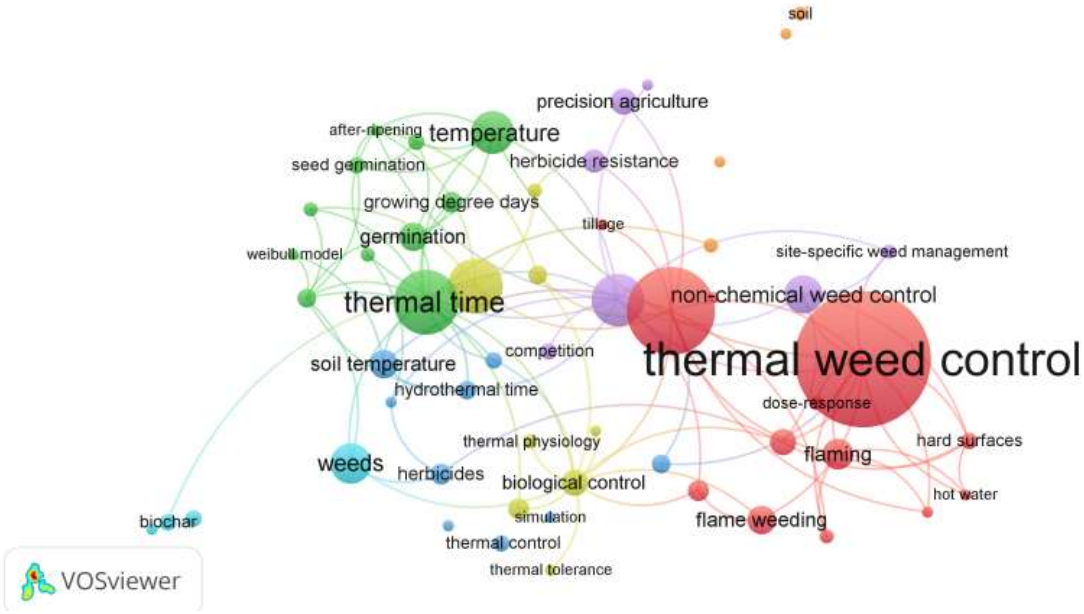


Şekil 10. Anahtar kelimelerin dendrogramı

Hiyerarşik kümeleme analizine göre termal yabancı ot kontrolü alanındaki anahtar kavramlar birkaç temel grup altında toplanmaktadır. İlk büyük kümede flame weeding (alevle yabancı ot kontrolü), weed control (yabancı ot yönetimi), thermal(termal), flaming (alevleme) gibi kavramlar yer almakta olup, bu grup alevleme yöntemiyle ilgli tehditler ve yabancı ot yönetimini temsil etmektedir. İkinci kümede thermal time (termal zaman), germination (çimlenme), temperature (sıcaklık), soil (toprak), weed management (yabancı ot yönetimi), weeds (yabancı otlar) bulunmakta ve çimlenme öne çıkarmaktadır. Üçüncü kümede non-chemical weed control (kimyasal olmayan yabancı ot kontrolü), integrated weed management(entegre yabancı ot yönetimi), control (kontrol), thermal weed control (termal yabancı ot kontrol) ve weed (yabancı ot) gibi kavramlar toplanarak yenilikçi yaklaşımlar ile termal yabancı ot kontrol stratejilerinin kesişimini göstermektedir (Şekil 10). En fazla kullanılan anahtar kelimeler Şekil 11'de gösterilmiştir.

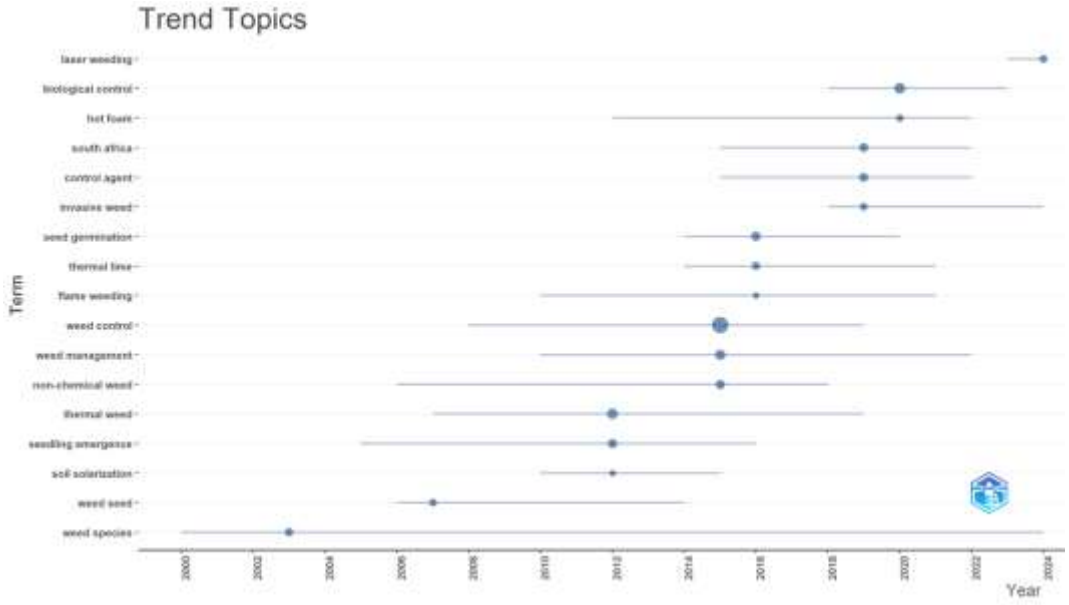
Şekil 11. En sık kullanılan anahtar kelimeler

Yabancı ot bilimi alanındaki termal yabancı ot yönetimi araştırmalarının odak noktalarını açıkça göstermektedir. En büyük ve en sık kullanılan kavramlar arasında ‘’thermal weedcontrol’’,weed control, weed,temperature, management,thermaltime, germination, growht, emergnce, yield, soil, dormancy, herbicides, non-chemical weed control, flaming, flame weeding, herbicide resistance ve herbicide’’ yer almaktadır (Şekil 11). Anahtar kelimeler, bir literatürün altta yatan araştırma yönünü temsil eden ifadelerdir. Sonuç olarak, anahtar kelime analizi araştırma konularının haritalanmasını sağlar ve belirli bir bilimsel alandaki araştırma yönünü ve boşlukları tespit etmeye yardımcı olur (Xiang ve ark., 2017; Jimoh ve ark., 2022).Anahtar kelimelerin ağ haritası Şekil 12’de verilmiştir.



Şekil 12. Anahtar kelime ağı haritası

Anahtar kelime ağı incelendiğinde, araştırmaların birkaç ana tema etrafında yoğunlaştığı görülmektedir. Kırmızı küme, *‘’*thermal weed control,non-chemical weed control, flaming,flame weeding,hot water,hard surfaces’’ gibi kavramlar etrafında şekillenmiştir. Bu küme, kimyasal olmayan ve özellikle ısıl yöntemlerle (alev, sıcak su) yapılan yabancı ot kontrolünü konu almaktadır. Yeşil küme**,** *‘’*thermal time, germination,temperature, growing degree days, seed germination’’ gibi terimlerle çimlenme süreçleri ve büyüme derecesi günleri üzerinden fizyolojik süreçleri temsil etmektedir. Mavi küme**,** ‘’weeds, herbicides, biological control, thermal tolerance, weed biology’’ gibi kavramlarla hem kimyasal hem de biyolojik mücadele yöntemlerini öne çıkarmaktadır. Mor küme**,** ‘’precision agriculture, site-specific weed management, herbicide resistance’’ terimleriyle teknolojik ve hassas tarım yöntemlerine odaklanmaktadır. Sarı küme ise *‘’*soil temperature, hydrothermal time, thermal physiology*’’* gibi kavramlarla toprak sıcaklığı ve ısının fizyolojik etkilerini temsil etmektedir. Termal yabancı ot mücadelesi konusundaki akademik literatürün hem teknik hem de biyolojik yönleri kapsadığı anlaşılmaktadır. Konu sadece uygulama teknikleriyle sınırlı kalmayıp, aynı zamanda bitki fizyolojisi, çevresel faktörler ve yönetim stratejileriyle de güçlü bir şekilde ilişkilidir (Şekil 12). Trend konu başlıkları şekil 13’te verilmiştir.



Şekil 13. Trend konuların ağ analizi

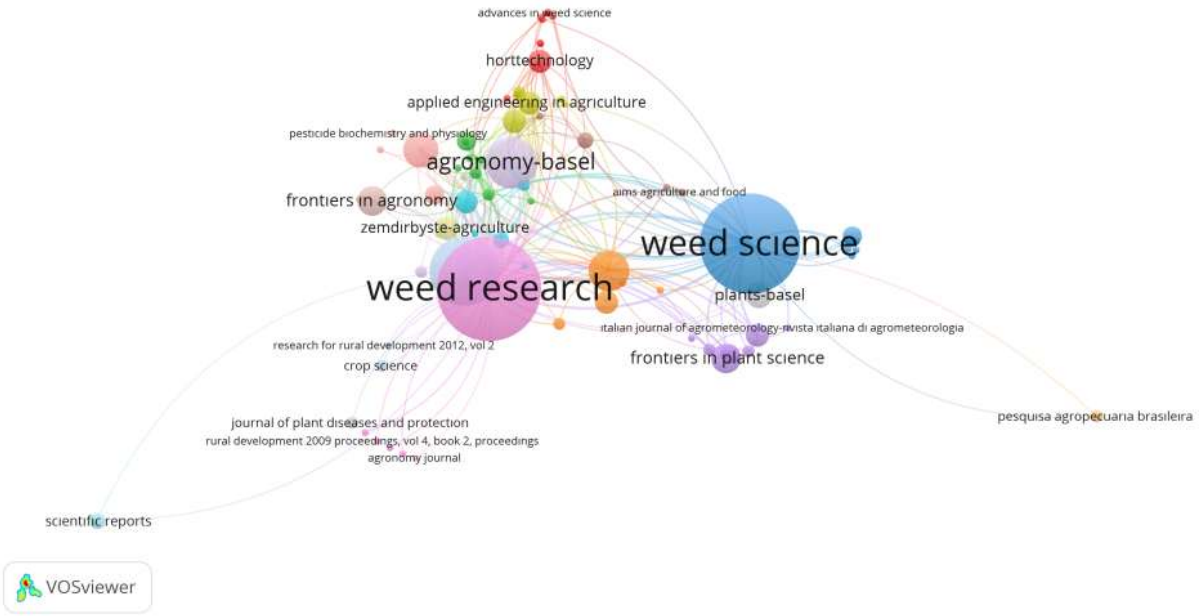
Termal yabancı ot mücadelesine yönelik araştırma temalarının zaman içinde belirgin bir dönüşüm geçirdiği görülmektedir. 2000'li yıllarda çalışmalar daha çok yabancı ot türleri ve toprakla ilişkili yöntemlere (weed species, weed seed, soil solarization) odaklanırken, 2010'larda ısı etkisi, çimlenme süreçleri ve yönetim (thermal time, seed germination, flame weeding, non-chemical weed, thermal weed, weed management) stratejileri öne çıkmıştır. 2020'lerde ise**,** teknoloji ve yenilik temelli yöntemler (leser weeding, hot foam,thermal time**,** ve precision control**)** dikkat çekmiş; böylece termal yabancı ot kontrolü, hassas tarım ve sürdürülebilirlik perspektifinde yeniden tanımlanmıştır. Bu dönüşüm, alanın başlangıçta uygulamalı ve tür odaklı çalışmalardan, zamanla biyolojik süreçlere ve nihayetinde teknoloji tabanlı yenilikçi çözümlere doğru evrildiğini açıkça ortaya koymaktadır (Şekil 13). En fazla yayım yapılan dergiler Tablo 4'te verilmiştir.

Tablo 4. En fazla yayım yapılan dergiler

Dergiler	**h_index**	**AS**	**YS**	**BY**
Weed Research	16	1255	40	1991
Weed Science	15	1010	38	1993
Weed Technology	10	271	23	1996
Biological Control	8	171	10	2002
Crop Protection	8	255	11	2002
Agronomy-Basel	6	129	15	2019
Entomologia Experımentalis Et Applicata	6	152	7	2007
Frontiers in Plant Science	6	94	7	2016
Acs Sustainable Chemistry & Engineering	5	259	5	2017
Biosystems Engineering	5	153	5	2003
Field Crops Research	5	485	5	1999
Frontiers in Agronomy	5	85	7	2021
Pest Management Science	5	96	9	2004
Applied Engineering in Agriculture	4	54	5	2009

AS; atıf sayısı, YS; yayın sayısı, BY; başlama yılı

En fazla yayın yapılan dergiler arasında ilk sırada Weed Research (40 yayın, 1255 atıf, h-indeks: 16) yer almakta, onu Weed Science (38 yayın, 1010 atıf, h-indeks: 15) takip etmektedir. Bu durum, termal yabancı ot kontrolü araştırmalarının daha çok yabancı ot bilimi odaklı uzmanlık dergilerinde yayınlandığını göstermektedir. Üçüncü sıradaki Weed Technology (23 yayın, 271 atıf, h-indeks: 10) de yine aynı alana özgü bir dergi olup, ilk üç dergi toplam yayınların çok büyük bir kısmını barındırmaktadır. Termal yabancı ot kontrolü araştırmalarının öncelikle alanın uzman dergilerinde yoğunlaştığını**,** fakat zamanla tarım, biyoloji, mühendislik ve sürdürülebilirlik odaklı dergilere yayıldığını göstermektedir (Tablo 4). Dergilerin ağ grafiği analizi Şekil 14'te gösterilmiştir.



Şekil 14. Dergilerin ağ grafiği analiz

Dergiler arası işbirliği ağının analizi, alanda belirgin kümelenmelerin oluştuğunu ortaya koymaktadır. Weed Research ve Weed Science dergileri merkezi bir konumda yer almakta olup, hem en yüksek yayın hacmine sahip hem de güçlü bağlantılara sahip merkezi dergiler olarak öne çıkmaktadır. Yeşil küme, Agronomy-Basel, Frontiers in Agronomy *ve* Applied Engineering in Agriculture gibi dergileri içermekte olup, tarım ve mühendislik boyutuna odaklanan bir topluluğu temsil etmektedir. Mavi küme, özellikle Weed Science çevresinde şekillenmiş olup, yabancı ot bilimi alanına özgü klasik araştırmaları kapsamaktadır. Turuncu ve pembe kümeler ise Frontiers in Plant Science ve Crop Science gibi daha küçük ve spesifik dergilerden oluşmakta, disiplinler arası köprü işlevi görmektedir. Bu yapısal dağılım, termal yabancı ot kontrolüne ilişkin yayınların başlangıçta Weed Science literatürü çerçevesinde yoğunlaştığını, ancak zamanla tarım, biyoloji ve mühendislik odaklı dergiler aracılığıyla disiplinler arası etkileşimler geliştirdiğini ortaya koymaktadır. Dolayısıyla, alanın gelişimi hem uzmanlaşma eğilimleri (yabancı ot odaklı dergiler) hem de genişleme eğilimleri (tarım ve mühendislik odaklı dergiler) doğrultusunda paralel bir gelişim göstermektedir (Şekil 14).

4. Sonuç

Bu çalışma, termal yabancı ot kontrolüne ilişkin yayın eğilimlerini bibliyometrik bir çerçevede inceleyerek alanın gelişim dinamiklerini ortaya koymuştur. Bulgular, 1981'den itibaren sınırlı sayıda çalışma ile başlayan araştırma faaliyetlerinin, özellikle 2010'lu yıllardan itibaren belirgin bir artış eğilimi gösterdiğini ortaya koymaktadır. Yayın sayısındaki bu artışın, kimyasal içerikli yöntemlerin kısıtlanması ve çevre dostu alternatiflere yönelik artan

ilgi ile doğrudan ilişkili olduğu görülmektedir. Alan literatüründe önemli yazarlar arasında Fontanelli, M., Peruzzi, A., Frasconni, C. ve Raffaelli, M. ön plana çıkarken; Forcella, F. ve Melander, B. gibi sınırlı sayıda çalışma üreten ancak yüksek atıf etkisi yaratan araştırmacılar, alanın gelişimine farklı bir boyut kazandırmıştır. Son dönemde literatüre dâhil olan Bitarafan, Z., Chauhan B.S. ve De Cauwer, B. gibi yazarların ise gelecekteki araştırmalara yön verebilecek potansiyele sahip oldukları değerlendirilmektedir. Anahtar kelime analizi**,** "thermal weed control", "weed management", "non-chemical weed control", "flaming", "temperature" ve "thermal time" gibi kavramların öne çıktığını ve bunların alanın metodolojik ve kavramsal temelini oluşturduğunu göstermektedir. Konu dağılımı incelendiğinde, başlangıçta tarımsal üretime odaklanan çalışmaların zamanla kentsel alanlar, yol kenarları, parklar ve endüstriyel bölgeler gibi tarım dışı uygulama alanlarına yöneldiği görülmektedir. Bu durum, termal yöntemlerin yalnızca üretim verimliliği açısından değil, aynı zamanda çevresel sürdürülebilirlik ve ekonomik bakım maliyetlerinin azaltılması bakımından da stratejik bir öneme sahip olduğunu ortaya koymaktadır. Dergi analizi**,** araştırmaların başlangıçta Weed Research ve Weed Science gibi yabancı ot bilimi odaklı dergilerde yoğunlaştığını; zamanla tarım, biyoloji ve mühendislik temelli dergilerin de alana katkı sunduğunu göstermiştir. Bu eğilim, konunun disiplinler arası niteliğinin giderek güçlendiğini kanıtlamaktadır. Ayrıca disiplinler arası işbirliğinin artmakta olduğu ve termal yöntemlerin yalnızca tarımsal üretimde değil, kentsel ve çevresel yönetim uygulamalarında da araştırma konusu hâline geldiği belirlenmiştir. Yöntemsel açıdan ise alevleme, sıcak su, buhar ve mikrodalga gibi doğrudan ve dolaylı uygulamalar üzerinde yoğunlaşan çalışmaların, teknolojik yenilikler ve hassas tarım uygulamalarıyla bütünleşerek çeşitlilik kazandığı saptanmıştır. Bu çerçevede elde edilen bibliyometrik bulgular, yalnızca geçmişe dönük yayın eğilimlerini betimlemekle sınırlı kalmayıp, termal yabancı ot kontrolü alanında mevcut bilgi boşluklarının sistematik biçimde ortaya konulmasına ve gelecekteki araştırma önceliklerinin belirlenmesine de olanak sağlamaktadır. Özellikle enerji verimliliği, uygulama maliyetleri ve hedef dışı organizmalar üzerindeki potansiyel etkilerin bütüncül ve disiplinler arası yaklaşımlarla ele alınması, alanın uzun vadeli ve sürdürülebilir gelişimi açısından kritik bir gereklilik olarak öne çıkmaktadır. Bunun yanı sıra, yetkili kurumlar ve saha uygulayıcıları için yol gösterici nitelik taşıyan bu tür bibliyometrik analizlerin, çevre dostu ve kimyasal girdilere dayanmayan yabancı ot yönetim stratejilerinin benimsenmesini ve yaygınlaştırılmasına katkı sağlayacağı düşünülmektedir. Sonuç olarak, termal yabancı ot kontrolü; çevresel sürdürülebilirlik, tarımsal verimlilik ve yenilikçi teknolojilerin entegrasyonu açısından giderek önem kazanan bir araştırma alanıdır. Gelecekte, bu yöntemlerin etkinliğini artırmaya yönelik disiplinler arası çalışmaların ve uygulamalı saha araştırmalarının, literatürdeki bilgi birikimini daha da derinleştireceği öngörülmektedir.

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Conservation Challenges of Modern World Heritage in the Case of Brasília: The Misalignment of Modernist Planning with Contemporary Urban Realities

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Abstract

This research article critically examines Brasília, one of the most comprehensive examples of modern urban planning, within the context of modernism's theoretical foundations, the city's historical development process, and its UNESCO World Heritage status. The city, designed in line with modernism's principles of rationality, functionality, and progress, is now showing incompatibilities with social transformation, transportation dynamics, public space usage, and sustainability requirements. The study evaluates modern planning literature, archival and planning documents related to the founding of Brasília, and UNESCO monitoring and evaluation reports using qualitative content analysis methods. The findings reveal problem areas such as loss of functionality in symbolic areas such as the Monumental Axis, weakening of pedestrian-oriented design in the Superquadra settlement model, failure of public spaces to respond to social needs, and inadequacy of current planning approaches that take ecological sensitivity into account. The study demonstrates that maintaining only formal integrity is insufficient for preserving Brasília's modern heritage; a holistic conservation approach that incorporates user needs, accessibility criteria, and sustainability principles is essential. In this context, realigning modern planning principles with contemporary urban living practices is critical for both the continuity of Brasília's heritage value and the future transformation of modern cities.

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1. Introduction

Modernism is accepted as a comprehensive cultural paradigm that emerged in Europe in the late 19th century and led to fundamental transformations in architecture, art, urban planning, systems of thought, and social life. As Frampton (2020) states, modernism represented a break from historical aesthetic and traditional architectural understandings; it created a new spatial and intellectual framework centered on rationality, functionality, technology, and the ideal of progress. Modernity, on the other hand, is understood as the reflection of this intellectual transformation on social structures, economic relations, and life practices; it is shaped by industrialization, mass production, urbanization, and scientific developments (Giddens, 1990). In this context, the impact of modernism on the disciplines of architecture and urban planning led to radical spatial transformations throughout the 20th century.

The modern approach in architecture and urban planning is defined by functional zoning, simple geometric forms, spatial arrangements based on social reform ideas, opposition to ornamentation, and rational planning principles. According to Curtis (1996), modern architecture is not merely an effort to produce formal innovation but also carries the claim of representing social progress spatially. Principles urban planning approach advocated the reorganization of urban life according to more orderly, healthy, efficient, and "rational" principles; in this context, principles such as wide boulevards, open green space systems, functional zoning decisions, and mass housing production have been decisive in many modern urban plans.

The strengthening of the view that modern architectural products have cultural heritage value since the second half of the 20th century has brought about important debates in conservation theory. Choay (2001) emphasizes that modern heritage cannot be evaluated using traditional conservation principles and that concepts such as authenticity, integrity, material continuity, and ideological representation need to be redefined in different ways in the context of modern architecture. Modern architectural heritage has become a multidimensional type of heritage not only because of its physical characteristics but also because of its layers such as modern state ideology, claims of social reform, construction of national identity, and representational power (ICOMOS, 2013). With UNESCO WHC (World Heritage Centre) beginning to include modern heritage sites on the World Heritage List, the preservation of modern cities, continuity of use, sustainability, and accessibility have become one of the priority areas of discussion in international conservation literature.

Brasília considered one of the most comprehensive applications of modernism in the world. The city was founded in 1960 as Brazil's new capital; with Lúcio Costa's Pilot Plan and Oscar Niemeyer's monumental buildings, it became a comprehensive spatial manifesto of modern design (Holston, 1989). The city plan, which resembles an airplane from a bird's eye view, presents a symbolic design approach that encompasses the construction of national identity, the ideal of modernization, and the spatial representation of central administrative power. Brasília was included in the UNESCO World Heritage List in 1987 as one of the most consistent and complete applications of modern principles at the city scale; in this respect, it is recognized as having outstanding universal value as "the first fully realized example of a modern capital city"

However, significant tensions have emerged in the alignment of modern planning approaches with the social, spatial, and environmental requirements of the 21st century. The literature indicates that the primary problems facing modern cities today include social fragmentation caused by functional segregation, vehicle-oriented transportation systems limiting pedestrian mobility, the weakening of effective use of public spaces, incompatibility with sustainability principles, and the inadequacy of heritage protection legislation in practice

(Scifoni, 2015). In the specific case of Brasília, these problems manifest themselves in the loss of functional diversity of the Monumental Axis, the inability of the Superquadra model to adapt to current user needs, the threat to the integrity of the heritage area posed by urbanization pressures, and the weakness of planning decisions requiring ecological sensitivity.

This study aims to critically examine Brasília, which falls under the category of modern architectural heritage, within the context of the theoretical foundations of modernism, urban planning principles, and UNESCO World Heritage status. The main objective of the research is to reveal the points of incompatibility between modern ideals and contemporary urban living practices and to determine the components of a holistic approach necessary for the preservation of modern heritage. In this context, the main question of the research is formulated as follows: How can a holistic conservation approach be developed that brings together user needs, accessibility criteria, and sustainability principles for the preservation of Brasília's modern heritage value? In addition to this fundamental question, the extent to which modern planning aligns with contemporary urbanization dynamics, how the issues highlighted in UNESCO conservation reports can be managed, and how modern heritage can be made sustainable not only formally but also functionally and socially will be discussed. Thus, the study aims to contribute to the reassessment of modern cities within the current balance of conservation and use.

2. Material and Methods

This study is designed as a research project examining Brasília's modern urban planning approach and the current spatial, social, and environmental issues arising in the context of its UNESCO World Heritage status. The research is a single-case study; it takes Brasília as an exemplary "planned capital" where modern ideals are embodied and aims to analyze the tensions between these ideals and current usage practices. Within this framework, the methodology consists of literature review, document and report analysis, and descriptive and interpretive thematic analysis of these data.

The first stage involved a comprehensive literature review on modernism, modernity, modern urban planning, planned capitals, heritage conservation, and sustainable planning approaches. In this context, fundamental sources on architecture and urban planning theory, theoretical texts addressing the historical background of modernism and its relationship with urbanization processes, and current academic studies analyzing examples of modern cities were evaluated. Publications discussing the effects of modern planning principles on public space, transportation design, functional zoning, and social life formed the backbone of the theoretical framework for the analysis of Brasília. In this process, studies that were not directly related to the subject or that offered a limited context were excluded; high-quality studies that addressed the spatial design of modern cities and heritage conservation debates together were preferred.

In the second stage, official documents, planning decisions, and international reports related to Brasília were systematically examined. UNESCO's monitoring and conservation reports evaluating Brasília as a World Heritage site were used as fundamental reference sources to reveal the points of incompatibility between the goal of preserving the city's modern integrity and user needs, social change, and sustainability demands. In addition, local-scale planning documents related to the city's urban development, plan revisions, transportation, and open space arrangements were evaluated as secondary data in the analyses. Components such as the Monumental Axis, Superquadra settlement model, open and green space system, and pedestrian and vehicle transportation design were examined through both plan notes and critical academic studies related to these documents. At this stage, data produced by different institutions were considered comparatively, considering the principles of data diversity, consistency, and comparability.

In the third stage, qualitative content analysis and thematic analysis were applied to the data obtained from the literature and document review. First, an evaluation framework was established based on modern planning principles, heritage conservation approaches, and sustainability criteria. Within this framework, the urban space was conceptually structured under the following headings: (i) morphological integrity and symbolic structure, (ii) public space use and social interaction, (iii) transportation and accessibility, (iv) ecological sensitivity and open/green space system, and (v) heritage management and continuity. Subsequently, the problem areas identified specifically in Brasília were placed within this thematic framework and interpreted. Thus, the points of harmony and disharmony between modern ideals and current spatial practices were evaluated not only formally but also in terms of their social and functional dimensions.

Thanks to this methodological approach, Brasília's modern heritage quality is addressed not only as a registered "object" but also as a living urban environment and the spatial stage of constantly changing social practices. The extent to which modern design overlaps with today's discussions on sustainability, accessibility, and publicity is questioned, forming the theoretical basis for the assessments presented in the following sections.

3. Results and Discussion

3.1. Brazil's historical background

Brazil's historical development has a multi-layered structure, beginning with indigenous cultures dating back thousands of years, followed by European colonization, the imperial period, the founding of the republic, and modernization processes. Archaeological evidence shows that human settlements existed in Brazil at least 11,000 years ago. The "Luzia Woman" discovered in the Minas Gerais region is considered one of the oldest humans remains in South America and proves that the region has been inhabited since the Paleolithic period (Neves & Hubbe, 2005). Pottery found in the Amazon basin reveals that communities in the region had a developed production culture 8,000 years ago (Roosevelt, 1999). Contact with Europe began in 1500 with the arrival of Portuguese navigator Pedro Álvares Cabral on the continent, marking the beginning of Brazil's approximately three-century-long period of Portuguese colonization (Schwartz, 1985). The first colonial activities were based on the trade of pau-brasil (Brazil wood), which also gave the region its name. This tree species, which was in high demand in Europe for obtaining red dye, was intensively exploited in the 16th and 17th centuries, and smuggling and pirate attacks significantly affected the region's economic and political structure (Dean, 1995). In the 17th and 18th centuries, Brazil became a stage for colonial rivalry; in particular, the Dutch occupation of the Pernambuco region and the conflicts between 1648 and 1654 were critical processes that determined the political control of the region. The 1750 Treaty of Madrid redrew the borders between Portugal and Spain, leaving most of the colonial territories in South America to Portugal (Prado, 2014). The 18th The 19th century was a turning point in Brazilian history. In 1807, the Portuguese royal family moved to Rio de Janeiro due to Napoleon's invasion, making the city the capital of the Portuguese Empire for 13 years. During this period, Brazil gained significant momentum in terms of economic and cultural development (Maxwell, 2003). Independence was declared in 1822 and, after two years of conflict, was recognized by Portugal in 1825, marking the beginning of the Brazilian Empire.

The late 19th century saw critical social reforms in terms of the country's social and political transformation. The abolition of slavery in 1888 made Brazil the last country in the Americas to abolish slavery. The following year, in 1889, the Brazilian Republic was proclaimed when Marshal Deodoro da Fonseca seized power. Throughout the 20th century, the country exhibited a governance structure that oscillated between military coups, political instability, and development programs. The Getúlio Vargas era, particularly between 1930 and

1945, stands out for its industrialization-based economic model and authoritarian governance (Skidmore, 1999). Between 1964 and 1985, the country was ruled under a military dictatorship, and the transition to democratic rule began in 1985 with the election of Tancredo Neves. The 1988 Constitution laid the foundation for Brazil's contemporary democratic structure. In the 21st century, Luiz Inácio Lula da Silva's presidency (2003–2010) drew attention with its social policies and economic growth; Brazil positioned itself as a rising economic actor on the global stage (Hunter and Power, 2007). This broad historical process formed the basis of modern Brazil's cultural and spatial structure; in particular, the establishment of the new capital Brasília in the mid-20th century has earned a special place in the country's history as a spatial expression of national identity, the ideal of modernization, and regional development goals.

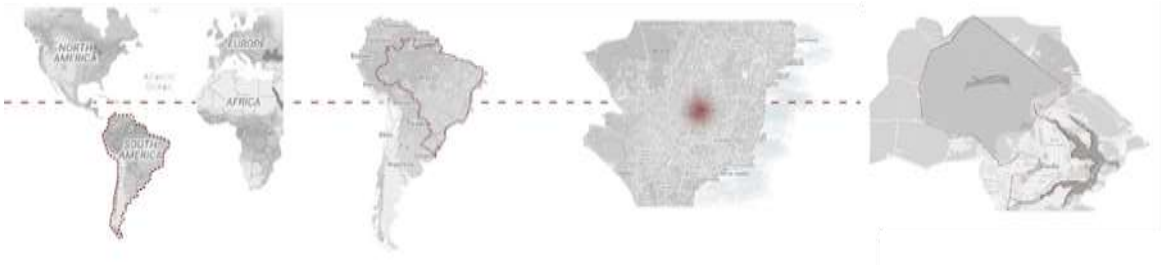

Figure1. The location of Brasília

Brasília is a modern capital city located within the boundaries of the Federal District (Distrito Federal), the center of the Federative Republic of Brazil. Geographically, it is built on the Brasília Plateau, located in the interior of the country at an altitude of approximately 1,100 meters. The city is a strategic settlement designed to boost development in the interior regions and strengthen national integration, located far from the country's coastline (Holston, 1989). Brasília's construction was completed in just 41 months, between 1956 and 1960. The city was officially declared Brazil's new capital on April 21, 1960, replacing Rio de Janeiro. As of 2021, the population living within the Federal District borders is 3,094,325, and the city is currently the country's administrative and symbolic center (Instituto Brasileiro de Geografia e Estatística-IBGE, 2021). The modern city of Brasília has a unique planning concept designed by urban planner Lúcio Costa and chief architect Oscar Niemeyer. The city plan developed by Costa is based on two main axes, evoking the shape of an airplane or a cross when viewed from above (Nobre, 2017).

• The east–west axis (Monumental Axis): brings together federal government buildings such as the Alvorada Palace (Presidential Residence), the Supreme Court (Supremo Tribunal Federal), the Chamber of Deputies (Câmara dos Deputados), and the Senate (Senado Federal). This axis has a monumental public space layout that spatially represents state power.

• North–south axis (Residential Axis): It contains the functional fabric that constitutes the city's daily life, with residential superblocks, commercial areas, service areas, and collective living units. Costa's "superquadra" concept stands out as the fundamental design component of planned and standardized residential units that organize modern urban life horizontally (Ferreira, 2005).

This planned and symbolic structure of the city offers a comprehensive interpretation of modern architecture and modern urban design principles. Brasília's location, as shown in Figure 1 and urban planning serve as an important example in international literature as a concrete spatial expression of Brazil's 20th-century modernization ideals (UNESCO, 1987).

3.2. Founding figures of the modern capital brasília

Lúcio Marçal, Ferreira Ribeiro, Lima Costa (1902–1998) is considered one of the most influential figures in modern Brazilian architecture and urban planning as we can see them in Figure 2. Born in Toulon to a Brazilian family, Costa continued his education in England and Switzerland, graduating from the Escola Nacional de Belas Artes in Rio de Janeiro in 1924 (Kessel, 2010). Although he produced works in an eclectic style in the early stages of his career, he became one of the pioneers of the modern architecture movement in Brazil after 1929, when he embraced modernism.

His collaboration with Gregori Warchavchik in the 1930s was a critical turning point in the institutionalization of modern architecture in Brazil. Costa took over as director of the National School of Fine Arts (ENBA) during the same period but was removed from office due to his reformist views (Mindlin, 1999). Costa joined the newly established National Historical and Artistic Heritage Service (SPHAN) in 1937 and played a decisive role in shaping the institution's architectural heritage policies for many years.

Lúcio Costa's architectural approach was characterized by a synthesis that reconciled traditional Brazilian building techniques with modern principles. The 1939 New York World's Fair Brazil Pavilion, designed in collaboration with Oscar Niemeyer, was one of the important projects that increased the international visibility of Brazilian modernism (Goodwin, 1943). In addition, structures such as the Parque Guinle residential complex, the Hotel São Clemente in Nova Friburgo, and the Ministry of Education and Health (MEC) building are major works that reflect his understanding of modern architecture.

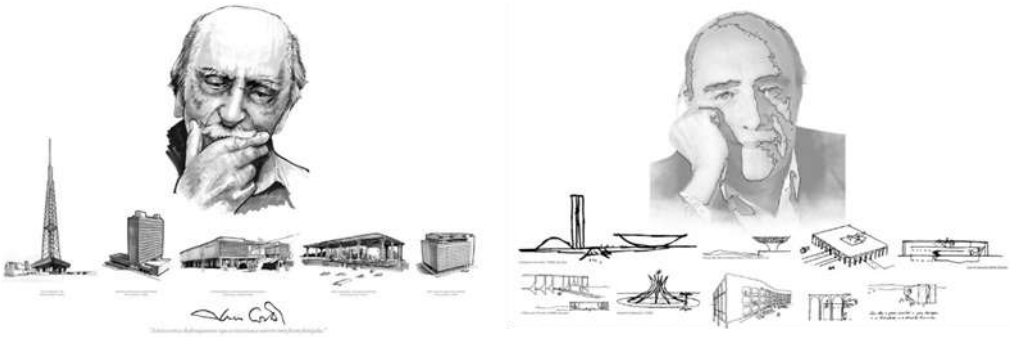

Figure2. Founding Figures of the Modern Capital Brasília

Costa's most important contribution is undoubtedly the Pilot Plan for Brasília. Having won the international competition launched in 1957 to design the new capital, Costa conceived the city around two main axes, evoking the shape of an "airplane" or a "dragonfly." Integrating the Monumental Axis and the Settlement Axis, this plan brings together the social, aesthetic, and functional principles of modern urban design in a holistic approach (Holston, 1989). Costa has earned a unique place in the history of modern urban planning with Brasília. Oscar Ribeiro de Almeida Niemeyer Soares Filho (1907–2012) is considered one of the most original and influential representatives of 20th-century modern architecture. Born in Rio de Janeiro, Niemeyer completed his architectural education at the Escola Nacional de Belas Artes and began his career in the studio of Lúcio Costa and Carlos Leão (Bruand, 2001).

Niemeyer's contribution to modern architecture, with its curved forms, fluid geometries, and sculptural approach to building, made a huge impact internationally. His participation in the 1936 project for the Ministry of Education and Public Health (MEC) building, under the direction of Lucio Costa, ensured his powerful entry onto the modern architecture scene. The

sections designed by Niemeyer were one of the important steps representing Brazilian modernism on the international stage.

The design of the Brazilian pavilion at the 1939 New York World's Fair increased his international recognition. His selection for the design team of the United Nations Headquarters in 1947 made Niemeyer one of the most important actors in global modern architecture. However, his leftist views and membership in the Brazilian Communist Party led to political pressure, particularly during the 1964 military dictatorship; due to these conditions, he moved to Paris in 1965 and continued his work in Europe and North Africa (Frampton, 2020).

Throughout his career, Niemeyer developed not only architectural structures but also furniture designs and spatial arrangements on an urban scale. The University of Algiers, the Mondadori Headquarters (Italy), and the French Communist Party Headquarters are some of his international works. However, his most iconic work is undoubtedly the public buildings of Brasília. Buildings such as the Planalto Palace, the National Congress Building, the Itamaraty Palace, and the Brasília Cathedral are considered masterpieces representing the sculptural and symbolic power of modern architecture (UNESCO, 1987).

Niemeyer's famous approach that "architecture is invention" clearly reveals the central role of creativity, social responsibility, and aesthetic sensitivity in his design philosophy. Niemeyer, who continued to produce until his death in 2012 at the age of 104, was a decisive figure in Brasília becoming the only modern capital city to be included on the UNESCO World Heritage List.

The founding process of Brasília is considered one of the most radical and comprehensive applications of 20th-century modern urban planning. The city was built between 1956 and 1960 under the framework of then-President Juscelino Kubitschek's "5 years of development in 50 years" policy, with the aim of developing the country's central regions and achieving national integration (Holston, 1989). Lucio Costa's urban design, called Plano Piloto, and Oscar Niemeyer's modern architectural approach made Brasília not only a new capital but also a spatial representation of the modern nation-state ideology.

Costa's city plan, when viewed from above, evokes a slightly curved cross shape, or, according to a more widely accepted interpretation, the figure of an airplane or a dragonfly. This form aimed to give the city a functional hierarchy; the Monumental Axis, running along the long East-West direction, contained the state center, including the executive, legislative, and judicial buildings; while the North-South settlement axis housed residential areas, social facilities, and daily life functions (Scott, 2013). The wide perspective on the Monumental Axis highlights large-scale architecture that emphasizes state power, while the settlement axis is planned on a more human scale.

In Costa's design, residential areas are organized in the form of "superblocks" (superquadras). Each "neighborhood unit" (unidade de vizinhança), consisting of four superblocks, was designed to meet the basic requirements of daily life, such as schools, places of worship, small commercial units, health centers, green spaces, and cultural venues (Mumford, 1961). This model embodied a modern social ideal that aimed to bring together different socio-economic classes to live in similar spaces. Indeed, it was often stated in the discourse of the time that having congressmen and their drivers living in the same superblock would be a "spatial symbol of a new and egalitarian society" (Holston, 1989).

The primary criticism of Brasília's spatial organization is the lack of pedestrian mobility created by modernism's rigid zoning principles. The city lacks a traditional street fabric; buildings are separated by wide roads and open spaces. As there are limited paths designated for pedestrians, a large part of daily life has become dependent on car use. This situation has

been criticized by theorists such as Jane Jacobs, who evaluate urban life through "interaction on the street," as a fundamental flaw in the modern urban planning approach (Jacobs, 1961).

In the planning process of Brasília, the bird's-eye perspective, that is, reading the city from above, played a central role. This approach, which occupies an important place in Le Corbusier's modern planning concept, emphasizes the geometric purity and symmetrical order of space (Le Corbusier, 1935). Lucio Costa also initially presented his design as a simple cross and later transformed this drawing into a curved form on the horizontal axis. Costa's approach made it possible to organize the city in line with modern ideals.

However, the city's experience at ground level was not found to be as powerful as its bird’s eye view appeal. In 1974, Brazilian writer Clarice Lispector described Brasília as "a beauty that is coherent when viewed from above, but alienating when viewed from below," emphasizing that the city's unnatural structure reflected the tension between modern dreams and human experience. These criticisms reveal that Brasília's modern planning ideals represent both a success and a limitation.

Ultimately, the creation of Brasília is a unique experience where modern planning principles merged with a national project. Both its architectural integrity and urban design vision have made the city one of the most important examples in 20th-century planning history; because of these characteristics, it was included in the UNESCO World Heritage List in 1987.

3.3. Brasília on the world heritage list

Brasília's inclusion in the UNESCO World Heritage List in 1987 is a result of the international recognition of the city's multi-layered values, not only in terms of modern planning but also in its cultural, artistic, and natural context in Figure 3. As a completely planned and rapidly constructed capital city, Brasília is considered one of the most striking examples of 20th-century modernism embodied on an urban scale. This is directly related to the city's design by Lucio Costa and Oscar Niemeyer, who adapted Le Corbusier's principles of modern urbanism to the Brazilian context (Holston, 1989; UNESCO, 2024).

First and foremost, Brasília has been considered a turning point in the history of modern urbanism. The purpose of Brasília's founding was not to be part of an expanding metropolis or to reshape an existing urban structure; it was to create a new capital city on completely empty land, designed to rebuild the national identity. In this sense, although Brasília is compared to contemporary capitals such as Chandigarh in India, it is described as the pinnacle of modernism in terms of its scale, holistic planning approach, and symbolic nature (Pendlebury, 2013).

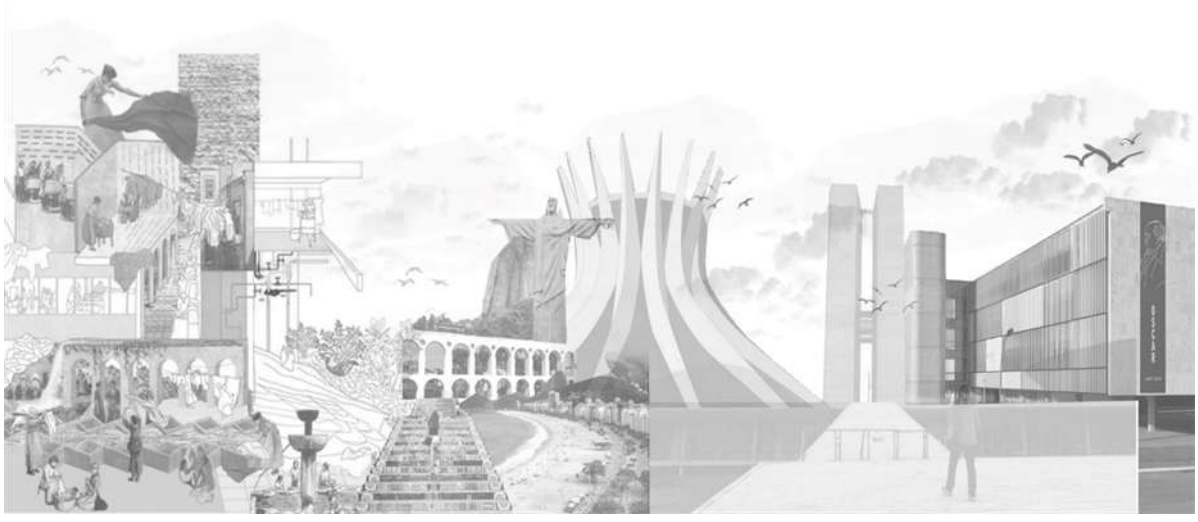

Figure3. Brasília on the World Heritage List

One of the most important factors contributing to the city's recognition by UNESCO is Brasília's highly integrated urban plan. Lucio Costa's Plano Piloto is based on two main axes in the shape of a cross and applies the fundamental principles of functionalist modernism—spatial hierarchy, separation of functions, reorganization of transportation, and large open spaces—on an urban scale. With these qualities, Brasília is one of the rare examples of modern urban planning theories put into practice (Scott, 2010).

Furthermore, the city possesses a superior architectural integrity thanks to Oscar Niemeyer's masterpieces. Monumental structures such as the National Congress, the Presidential Palace, the Supreme Court, and the cathedral represent the symbolic power of modern architecture and lend the city a universal aesthetic value. In this sense, Brasília's architecture is not only functional but also the product of an artistic vision (Frampton, 2020).

Another decisive factor in Brasília's protection by UNESCO is the city's cultural and artistic character. Sculptures, murals, and public art installations on a city scale reinforce the urban identity by supporting modern aesthetics. The city also serves as a socio-cultural laboratory, offering a spatial counterpart to new ways of life, collective use of space, and social modernization (Holston, 1989).

In terms of its natural context, Brasília is also ecologically important due to its location within the cerrado ecosystem. Rich in biodiversity, this region is in the transition zone between the Amazon, Prata, and São Francisco basins and plays a critical role in preserving the city's natural landscape (Silva and Bates, 2002). UNESCO also considers the harmonious coexistence of cultural heritage and the natural environment as part of its outstanding universal value.

In conclusion, the reasons for Brasília's inclusion in the World Heritage List are not limited to aesthetic and architectural achievements; the city is also internationally recognized as a multidimensional heritage site due to its innovative urban planning approach, ideals of social modernization, strong symbolic values, and rich natural environment.

3.4. Brasília's outstanding universal value, authenticity and integrity

Brasília is a city that comprehensively embodies the modern urban planning ideals of the 20th century and, in this respect, occupies an exceptional position among world heritage sites. Designed by Lucio Costa and Oscar Niemeyer, this modern capital is regarded not only as an administrative center but also as a spatial manifesto of modernization. Completed at an extraordinary pace between 1956 and 1960, Brasília is the most powerful symbol of President Juscelino Kubitschek's development program, known as the "plano de metas." The city offers both an ideological and spatial expression of the application of modern principles in a tropical geography (Holston, 1989).

Lucio Costa's Plano Piloto is a unique interpretation of modern urban planning, organizing the city around two main axes and creating a holistic spatial composition. The Monumental Axis forms a symbolic line where state institutions are located, while the residential axis includes quiet, landscape-integrated residential areas where modern life is organized through the superquadra form. Through these two axes, Costa aimed to achieve both the spatial representation of state authority and the construction of a modern order for individual daily life. The residential blocks rising above the pilotis reflect the fundamental principles of modern architecture, which lend lightness to the structure and open the ground floor to public use (Nobre, 2017).

Oscar Niemeyer's architectural work is one of the most powerful elements defining Brasília's modern identity. Niemeyer's use of concrete as a sculptural form language presents a unique aesthetic defined as a tropical interpretation of modern architecture. Buildings such as the National Congress, the Planalto Palace, the Supreme Court, and the Brasília Cathedral

occupy a privileged place in the history of modern architecture in terms of fluidity of form, geometric dynamism, and symbolic meaning production (Frampton, 2020). This architectural approach, combined with Costa's rational planning, makes Brasília one of the most comprehensive modern examples in world architectural history.

UNESCO's designation of Brasília as having outstanding universal value is based on two fundamental criteria. The first, criterion (i), emphasizes that the city is an exceptional expression of human creative genius. The design and construction process of Brasília is one of the rare examples of modern architecture and urban planning ideals being applied with the aim of building an entirely new national identity. The holistic composition created on both an urban and architectural scale presents modernism not only as an aesthetic choice but also as a political and cultural project (Goodwin, 1943).

Criterion (iv), the second criterion, demonstrates that Brasília is one of the most prominent and original examples of the application of the urban planning principles of the Modern Movement. The principles of the Athens Charter, such as functional separation, scale hierarchy, and transportation organization, have been consistently applied throughout the city. The Superquadra layout offers standardized spatial units for modern living, while the Monumental Axis creates a spatial representation of state power. Niemeyer's administrative and cultural buildings create a comprehensive system as the architectural counterparts of this modern urban fabric (UNESCO, 1987).

Brasília's uniqueness is notable for the fact that it has been largely preserved in both its urban plan and architectural fabric. The characteristic spatial components of the Plano Piloto—intersecting axes, functional sector layout, Superquadra residential buildings, extensive green spaces, and monumental administrative buildings—still make the ideals of the original design visible. The city's uniqueness criteria, as defined by UNESCO, are evaluated at monumental, residential, social, and pastoral scales, and this multi-layered approach forms the fundamental framework that guarantees the sustainability of Brasília's unique character (Nobre, 2017).

The integrity of the city is ensured by the preservation of both spatial and functional components. Legal protection provided by federal and local governments supports the scale integrity of the Plano Piloto. However, increasing population, housing demand, and urban pressures threaten the heritage area to a certain extent. Nevertheless, most interventions are developed in accordance with the principles of the modern plan; the green belt surrounding the city defines Brasília's spatial boundaries, protecting the modern design from external influences (Holston, 1989).

As a result, Brasília maintains its outstanding universal value as one of the most comprehensive, consistent, and holistically preserved modern capitals in the history of modern architecture and urbanism. The city is one of the rare examples where not only modern architecture but also modernization as a political ideal has been transformed into a spatial form. Therefore, the uniqueness and integrity of Brasília remain an important reference for modern architectural heritage conservation approaches today.

3.5. Brasília world heritage site map

Included in the UNESCO World Heritage List in 1987, Brasília holds a unique position internationally as a comprehensive example of modern urban design and 20th-century architecture. The conservation area defined within the city plan developed by Lucio Costa under the name Plano Piloto has a comprehensive cultural landscape quality, including monumental buildings, residential blocks, green spaces, public open spaces, and landscape arrangements (UNESCO, 2024). This asset map defines the areas where Brasília's modern principles are embodied with strong coherence at the spatial scale.

The Monumental Axis (Eixo Monumental), which forms the backbone of the city, is an urban axis where the main structures representing Brasília's administrative, political, and symbolic identity come together in a comprehensive order as we see in Figure 4. Designed by Oscar Niemeyer, the Planalto Palace (Palácio do Planalto) reflects the simple, fluid, and sculptural expressions of modern architecture as the center of executive power. One of the most important buildings located on this axis is the National Congress Building, which houses the Senate and the Chamber of Deputies. With its two characteristic domes and vertical towers, this structure has become a spatial symbol of modern aesthetics and national political representation (Frampton, 2020). The Palace of Justice (Supremo Tribunal Federal), with its curved columns and transparent facade, is one of the most prominent examples of Niemeyer's characteristic architectural language (Holston, 1989).

Figure4. The Monumental Axis (Eixo Monumental)

One of Brasília's most iconic structures, the National Cathedral (Catedral Metropolitana), with its concrete ribs in a hyperbolic paraboloid form, ranks among the pioneering examples of modern religious architecture. The JK Memorial, an important part of the city's political memory, offers a historical narrative as it is dedicated to Juscelino Kubitschek, who led the process of founding Brasília (Pendlebury, 2013).

The Superquadra housing units are also an important component of the UNESCO heritage site. Designed in line with Costa's understanding of the modern lifestyle model, these housing blocks, surrounded by wide green belts and housing schools, places of worship, small-scale commerce, and social service areas within the neighborhood unit, transform modern urbanization ideals into a holistic living environment (Scott, 2010). Superquadras are important not only for their architectural and textural characteristics but also for offering spatial counterparts to modern lifestyles.

The asset map covers not only the built environment but also Brasília's landscape elements and natural surroundings. The vegetation specific to the Cerrado ecosystem, water surfaces, recreational green areas, and protected natural areas within the city are considered integral parts of a holistic urban landscape within the framework of modern planning approaches. The preservation of the natural landscape is considered one of the fundamental elements of the site's outstanding universal value (Silva and Bates, 2002).

Around the Plano Piloto, which forms the modern core of Brasília, several rural and urban settlements dating from before the city's construction are also important components of the Federal District's cultural heritage. These areas include the Historic Center of Planaltina (1859),

the Historic Center of Brazlândia (1933), and old farms located in the Federal District (Sobradinho, Monjolo, Capão dos Porcos, Bela-Vista, Gama, Curralinho, Ponte Alta, etc.). Planaltina is the oldest urban center that existed before Brasília was built and, despite its current position as a satellite city, it has largely preserved the historical fabric of the region. The Federal District's natural heritage sites also occupy an important place on the asset map. Brasília National Park, Águas Emendadas Biological Reserve, IBGE Biological Reserve, Cabeça de Veado Biological Reserve (Botanical Garden), São Bartolomeu and Descoberto Environmental Protection Areas are included in this scope. These areas support an ecosystem-based conservation approach aimed at preserving the region's landscape diversity. In addition, the area surrounding Lake Paranoá, the Maranhão Basin, and other proposed reserve areas have been considered as additional conservation areas to strengthen the representativeness of the Cerrado biome. Some of the workers' camps built during the founding of Brasília have survived to the present day and are considered valuable early examples of modern architecture combined with wooden construction techniques. Vila Planalto, Vila Metropolitana, Candangolândia, and other worker settlements are living witnesses to both modern planning concepts and the social history of the city's construction process. Structures located in these areas, such as the Fátima Meryem Ana Church, the São José Operário Church, and the Julia Kubitschek School, are among the important early architectural examples from the founding period of Brasília.

In Figure 5 all these components demonstrate that the Brasília World Heritage Site Map represents not only modern planning but also the need to understand the region's historical settlements, natural landscape, social structure, and cultural diversity as a shared heritage. The joint assessment of the modern urban fabric with historical-rural settlements and the natural environment forms the basis of Brasília's multi-layered cultural landscape character. For this reason, Brasília has been recognized by UNESCO as one of the exemplary representatives of modern architecture, urban modernity, and cultural landscape integrity (UNESCO, 2024).

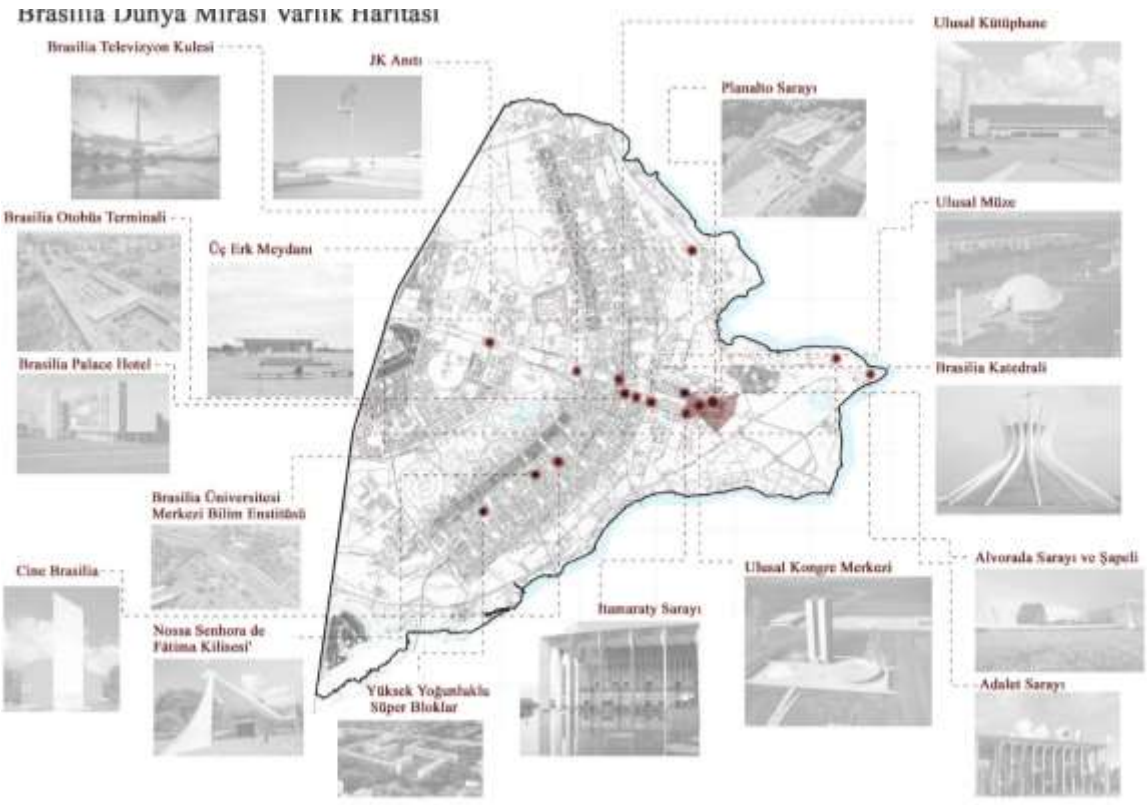

Figure5. Brasília World Heritage Site Map

3.6. Reading brasília UNESCO conservation status reports

It encompasses the area designed as Brazil's new capital and elements that bear witness to each stage of the Federal District's occupation process and the city's construction history. To ensure Brasília's legal protection, this area has been divided into three protection zones corresponding to different levels of control. These are mapped in Figure 6: 1. Special Protection Area (AIEsp) (Área de Interesse Especial de Preservação), 2. Buffer Zone (AAm) (Área de Amortecimento), 3. Protection Area (AIP) (Área de Interesse de Preservação). The special preservation area covers the monumental axis and the residential axis. This area is subject to strict regulations to ensure the integrity of Brasília. The buffer zone covers four areas adjacent to the monumental axis and the residential axis, providing a gradual transition to the special preservation area. The preservation area covers the entire pilot plan of Brasília, with emphasis on the preservation of iconic structures within the plan.

The monitoring of Brasilia under its UNESCO World Heritage status has been shaped by regular conservation status reports since the early 1990s. Initial assessments noted that the area known as El Polígono, which contains the city's core modern plan, had been preserved in its entirety despite rapidly increasing population pressure. UNESCO (1993) emphasized the need for the harmonious integration of urban development and heritage conservation objectives and welcomed Brazil's initiative to organize an international forum. The concept of "El Polígono" is used to describe the city's geometric layout and modern planning approach, symbolizing Brasília's departure from traditional urban models (Holston, 1989; UNESCO, 1993).

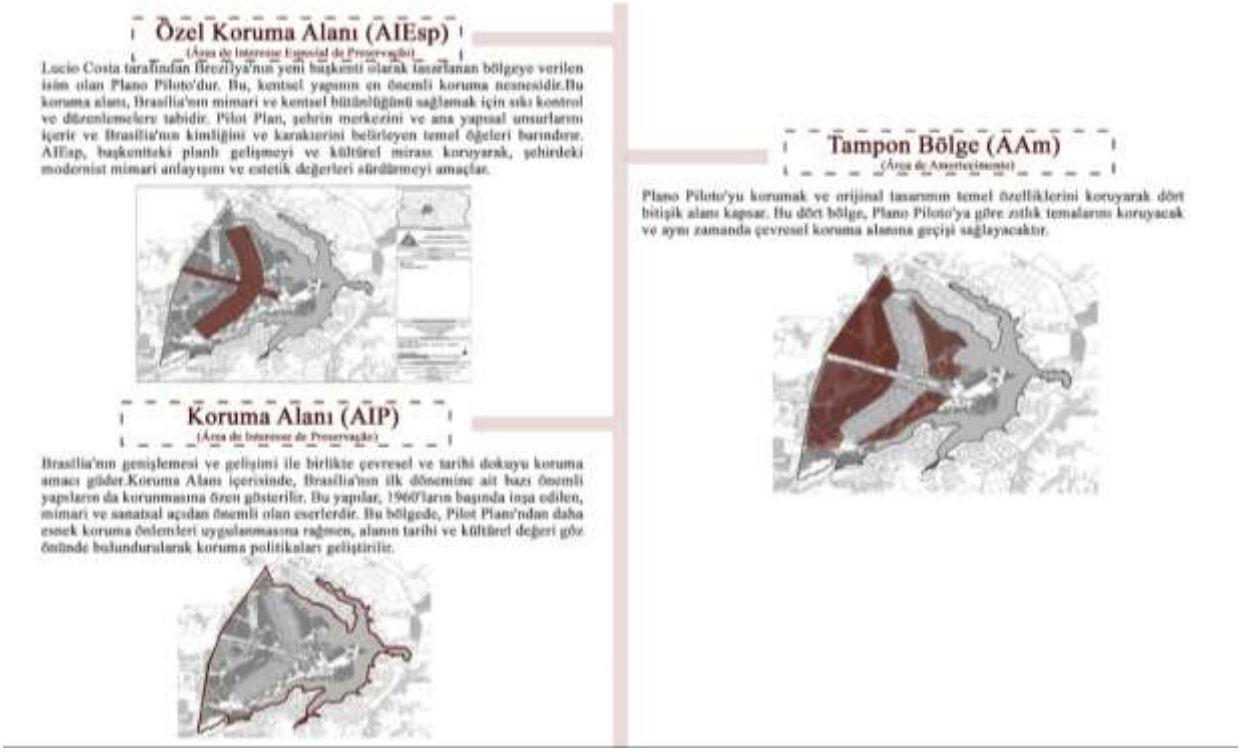

Figure6. Federal District's occupation process

By the early 2000s, UNESCO's assessments clearly revealed the new pressures facing the city. Brazilian representatives reported that strict regulations were being followed in all construction activities, but that the population had grown to several times the designed capacity, creating pressure, especially in the surrounding satellite cities. Despite this, UNESCO (2000) noted that the World Heritage value was being preserved in a holistic manner at the center.

Reports during this period also pointed out that the technical recommendations did not fully correspond to the situation on the ground.

The 2001 reports emphasized that the population of Plano Piloto remained stable, but rapid growth in the surrounding areas caused intense pressure on infrastructure and transportation (UNESCO, 2001). The lack of an effective public transportation system increased vehicle traffic within the protected area, posing a threat to spatial integrity. Therefore, the State Party proposed solutions such as awareness programs, an inventory of Plano Piloto, strengthening institutional capacity, developing conservation plans, and preparing a comprehensive Master Plan.

UNESCO noted that comprehensive technical studies were carried out during the 2003–2004 period, particularly regarding the protection of the natural environment, the regulation of the Paranoá Lake shoreline, and the preservation of the character of the Plano Piloto. The study "Coastal Characterization and Development Model" prepared for Lake Paranoá assessed the current threats to Costa's principles and provided guidelines that would form the basis for the Master Plan (UNESCO, 2004). During the same period, the study "Superquadra: Tempo e Espaço" detailed the conservation criteria for the use of residential blocks.

In the 2009 assessments, new urban development initiatives around Lake Paranoá, the lack of buffer zones, irregular changes in commercial areas, and the absence of a comprehensive Master Plan were identified as critical threats to heritage values (UNESCO, 2009). To address these issues, the Plano de Preservação do Plano Urbanístico de Brasília (PPCUB) was prepared, proposing new projects such as a tram line to solve transportation problems.

Reports from 2010 indicate that the Urban Complex Protection Plan was officially submitted and that the technical documentation for the W3 Boulevard and VLT line was sent to UNESCO. However, it was reported that the Orla Project on the Paranoá riverbank was restarted on a smaller scale, with the aim of restoring visual and physical integrity (UNESCO, 2010). Although new regulations were introduced for the South Trade Areas during this period, lack of oversight led to problems in implementation. In Vila Planalto, new planning initiatives were launched under the supervision of IPHAN to preserve the historical fabric.

The 2011 and 2012 reports stated that work on revitalizing W3 Boulevard had been halted, the VLT project had been suspended, and privatization pressures had increased along the shores of Lake Paranoá. These developments were found to be contrary to Costa's principle of public ownership of coastal use (UNESCO, 2011). It was also emphasized that the PPCUB had not been completed and that significant revisions were needed to the Land Management and Use Plans (UNESCO, 2012).

The 2019 reports stated that the misinterpretation of Brasília's four-scale structure (monumental, residential, social, pastoral) led to planning errors, particularly that the proposed increase in density in areas adjacent to the Monumental Axis threatened the heritage value (UNESCO, 2019). Therefore, the State Party was called upon to develop regular dialogue mechanisms with all relevant stakeholders.

The 2021 and 2023 evaluations reveal that the management preparation processes were disrupted due to COVID-19 and that the Management Plan has not yet been completed (UNESCO, 2021; UNESCO, 2023). In addition, the potential impacts on heritage values of proposals such as the redevelopment of the South Commercial Sector and the planning of a new neighborhood in the buffer zone were discussed. The 2023 report noted that some cultural artifacts were damaged during the political attacks on January 8, 2023, but that there was no structural damage to the buildings.

These processes demonstrate that the challenges faced in preserving Brasília as a modern world heritage site are not only related to physical deterioration but also to governance, planning, and social pressures. The general trend in UNESCO reports indicates that a comprehensive, participatory, and holistic approach to governance is essential for Brasília to sustain its values.

3.7. Brasília's problems

Despite being a comprehensive example of 20th-century modern urban design, Brasília, a modern capital city with UNESCO World Heritage status, currently faces various conservation issues at the spatial, administrative, social, and environmental levels. UNESCO's conservation status reports spanning 1993–2023 show that the city's problems are not limited to physical deterioration; they are fueled by multidimensional dynamics such as management processes, population pressure, dysfunctional modern spaces, and social transformation.

- The challenges facing Brasília can be discussed along four main axes:
- spatial functionality issues,
- socio-spatial inequality and excessive population pressure,
- environmental challenges and ecological threats,
- administrative and institutional inadequacies.

Although Brasília occupies a central position in 20th-century urban planning history as one of the most radical and comprehensive examples of modern urbanism principles, the incompatibility between the modern ideals that were implemented and current socio-spatial dynamics has led to the emergence of various structural problems over time. Lucio Costa's plan, based on a strict separation of functions, a car-centric transportation system that does not prioritize pedestrians, an idealized low-density spatial organization, and a relatively limited analysis of environmental conditions, has made fundamental problems such as transportation, accessibility, social inequality, ecological degradation, traffic congestion, and urban sprawl visible today (Epstein, 1973; Holston, 1989; UN-Habitat, 2019).

One of the most prominent problems in the city is the one-dimensional nature of its transportation infrastructure. Since the automobile was positioned as the primary means of transportation in Brasília's founding paradigm, pedestrian and bicycle transportation systems are secondary and, in most cases, neglected. Wide vehicle lanes, the disjointed location of functional areas, and the discontinuity of pedestrian paths significantly reduce accessibility in the city; for this reason, the city is often defined in the literature as a "car city" (Barbosa and Lima, 2017). Limited public transportation options and the system's lack of integration further reinforce dependence on private vehicles.

Functional segregation, one of the key components of Costa's modern plan, has created a rigid zoning structure in the city space; the physical separation of residential, administrative, commercial, and work areas has created the necessity for long-distance travel in daily life. This situation has limited social interaction areas, weakened public life, and caused spatial fragmentation (Scott, 1998). This model, with its sharp separation of functions, significantly conflicts with today's contemporary urban planning principles focused on mixed use.

Another major problem in the city is the socio-spatial inequality that has deepened over time. While the Plano Piloto, the core of Brasília, offers a modern lifestyle model designed for high- and middle-income groups, low-income groups have been directed to satellite settlements outside the city center with inadequate infrastructure and public services since the construction process (Holston, 2008). This situation has created a clear social divide in the city, making it difficult for spatial justice mechanisms to function.

Large-scale land interventions during the founding phase of Brasília led to the destruction of a significant portion of the Cerrado biome. The clearing of large areas for urban development resulted in the loss of vegetation cover and a decline in biological diversity in the region. The control of water flow through Lake Paranoá and various dam structures altered the natural hydrological cycle; the disruption of ecological corridors had negative effects on fauna. The increase in paved surfaces has also intensified the urban heat island effect (Ferreira and Silva, 2015).

Traffic and transportation systems have become an increasingly pressing issue in the city as population growth has far exceeded expectations. The transportation infrastructure, initially designed for 500,000 people, has become incompatible with rapid population growth; vehicle traffic has intensified, and urban mobility has become inefficient (UNESCO, State of Conservation Reports, 1993–2023). The limited availability of public transportation options has made private vehicle use a necessity, further exacerbating traffic problems.

Finally, Brasília's low-density structure and the rapid growth of new settlements far from the center have triggered uncontrolled urban sprawl. Sprawl has led to increased infrastructure costs, the formation of irregular settlements outside the planned core, and difficulties in the effective delivery of public services (Maricato, 2011).

All these problems are shown in Figure 7 demonstrate that Brasília's spatial design, idealized in modern planning, is not fully compatible with today's urbanization dynamics. There is a growing consensus that the city needs to be re-examined in line with the principles of sustainability, accessibility, and social inclusiveness.

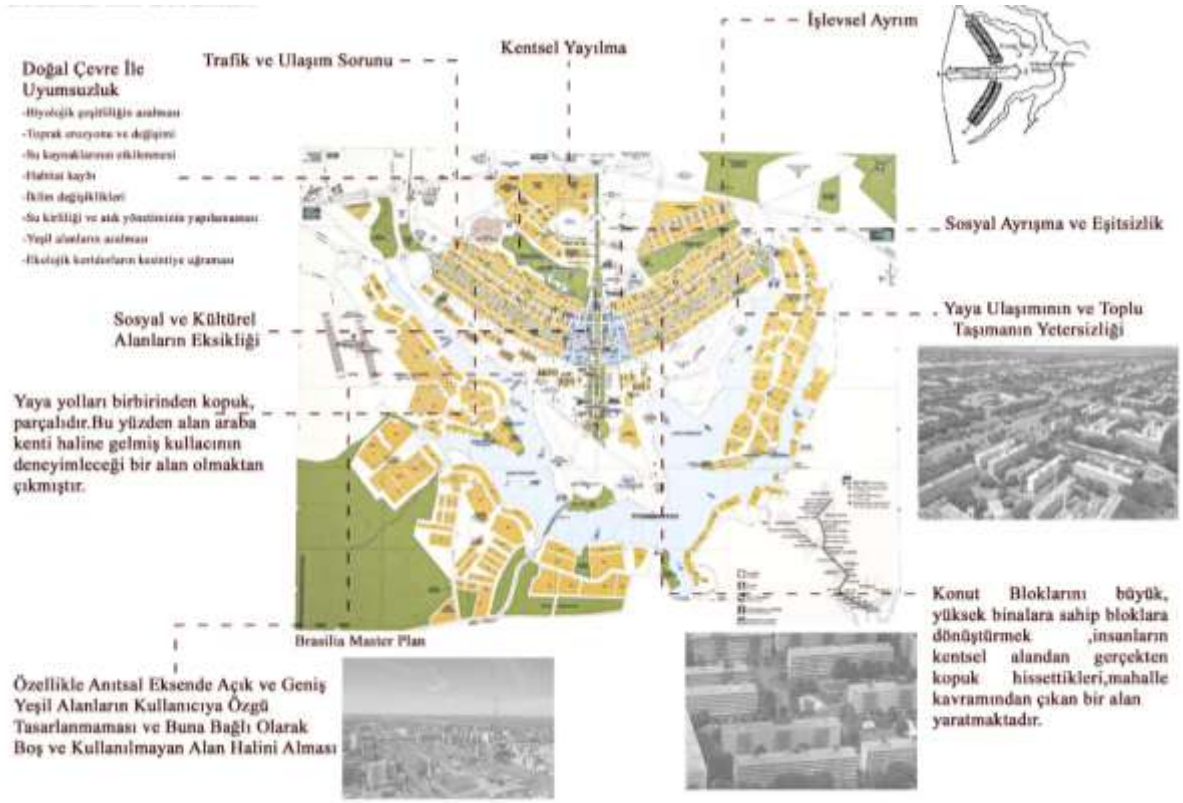

Figure7. Brasília's Problems

4. Conclusion

Although the element of water in the spatial design of the Modern City of Brasília, particularly around Lake Paranoá, has historically been considered an important landscape component, the city's current usage practices show that this potential has not been sufficiently functionalized. As noted in UNESCO's monitoring reports, public access issues, development pressure, and insufficient recreational areas along the shores of Lake Paranoá are among the fundamental problems weakening urban integrity (UNESCO, 2009; 2011). In this context, the proposed concept in Figure 8 aims to strengthen the physical and visual relationship between the lake and the city and increase user interaction with the water.

Within this scope, a pedestrian bridge connecting to the shore and adaptable modules for different functions have been designed. The modules have a flexible structure that can be rearranged according to changing usage scenarios and, in this respect, offer a dynamic usage potential that is an alternative to the static space understanding of modern planning. The triangular form was chosen to leverage this geometry's pressure resistance and structural stability, ensuring the modules can be used safely both on the water and along the shoreline. The market area and festival area have been designed using variable modules. The modules, which allow users to establish a physical and visual relationship with the water, have a structure that can be adapted to different scenarios and movements created in the x, y, z planes. The modules will be shaped according to the users in line with the actions.

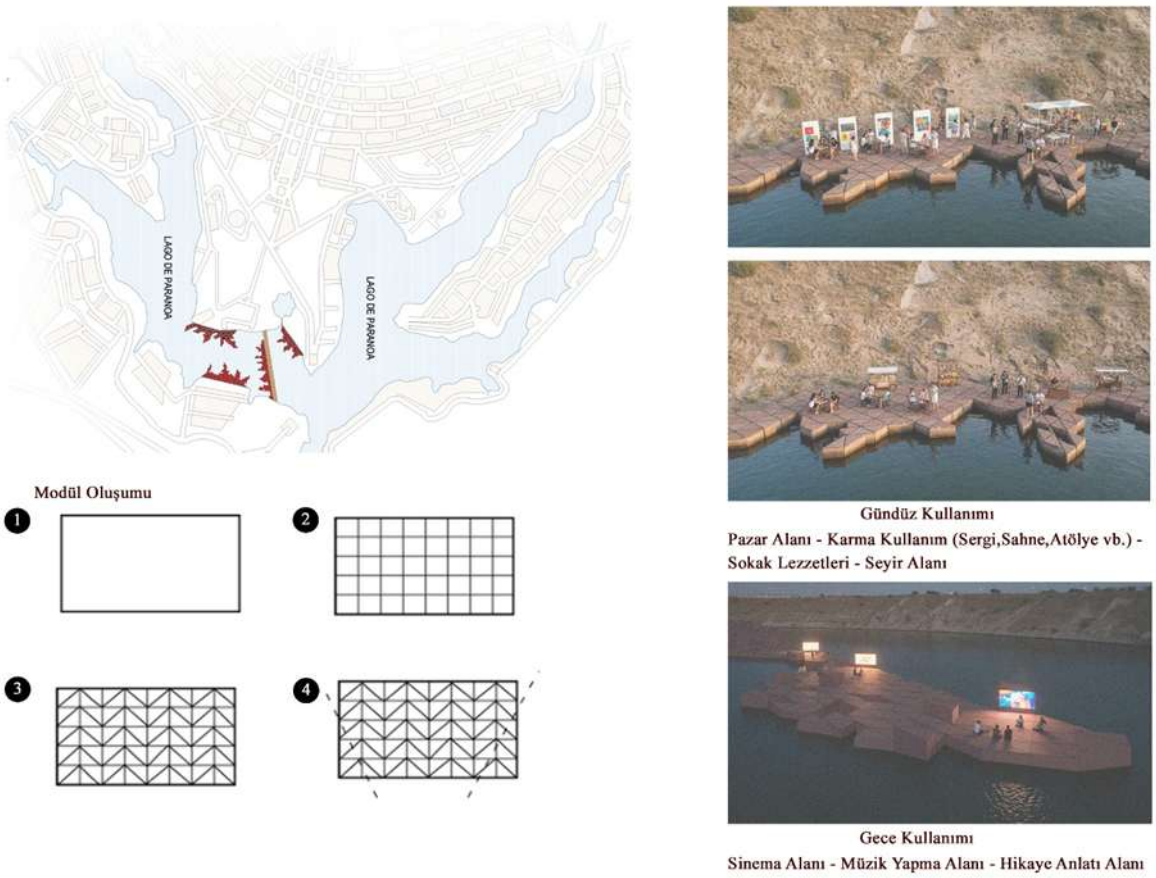

Figure8. Conceptual spatial scenarios 1

The reason for designing the modules in a triangular shape is that they have a structure adaptable to different scenarios and movements created in the x, y, z planes. Additionally, the triangle's high resistance to pressure and its ability to remain stable under pressure as a polygon contributed to its selection as the form to be used in relation to water.

The vast open spaces around the Monumental Axis, while central components of Brasília's modern planning, have become dysfunctional and underutilized spaces today. UNESCO conservation reports emphasize that the weak public use of this axis reduces the spatial vitality and that the area needs to be re-evaluated in terms of urban integrity (UNESCO, 2012; 2023). Criticizing the fact that such a large area is dysfunctional (not visited by users), it has been proposed that the area be given a "CULTURAL AXIS" function that supports the Monumental Axis and explains Brasília's symbolic importance, history, how it was founded, and its important buildings.In this context, the area will feature various functions as seen in Figure 9, such as open exhibitions, display areas, amphitheater seating areas, parks for children, and more.

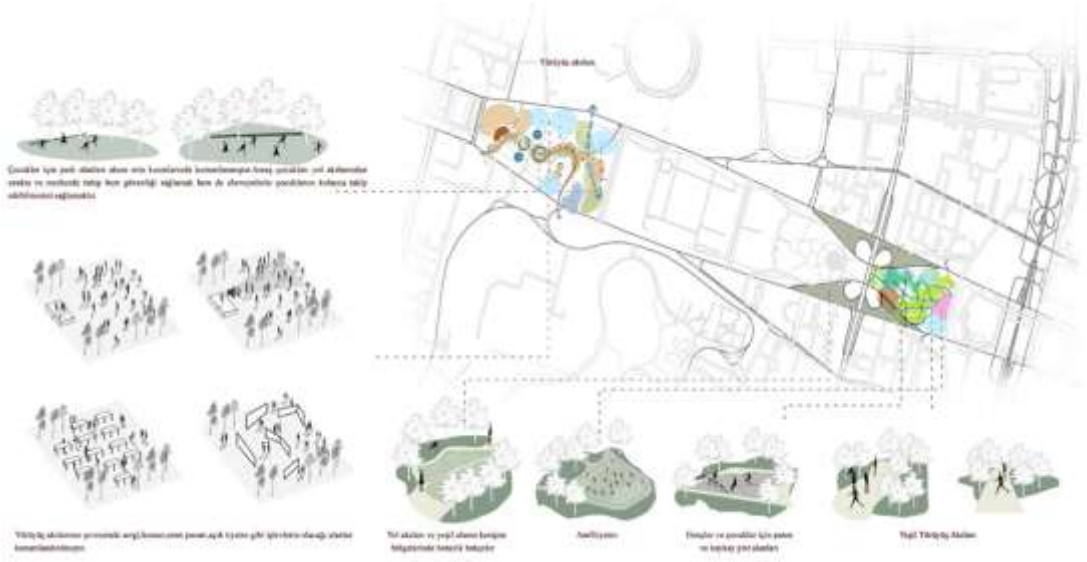

Figure 9. Conceptual spatial scenarios 2

The conceptual spatial scenarios developed in this context aim to reorganize superquadra units according to users' perceptual, spatial, and safety needs. The fundamental principles are to move parks and children's play areas away from vehicle traffic, reposition these areas in an integrated manner with pedestrian paths, and create spatial organizations that support parent-child interaction This idea is illustrated in Figure 10. Taking children's eye level as a reference is consistent with modern child-friendly city approaches and aims to transform the space into an experiential area that supports children's cognitive and sensory development (Kyttä, 2004).

Figure 10. Conceptual spatial scenarios 3

Activity and play areas located at the intersections of the proposed pedestrian routes create safe public spaces and strengthen social interaction within the Superquadra. While the current lack of pedestrian paths and heavy vehicle traffic limit safe usage areas for children and adults, the concept arrangement offers a comprehensive approach aimed at solving these problems, which are illustrated in Figure 11. Thus, while preserving Brasília's modern planning heritage, the goal is to create a more inclusive and livable environment that meets the needs of contemporary urban life.

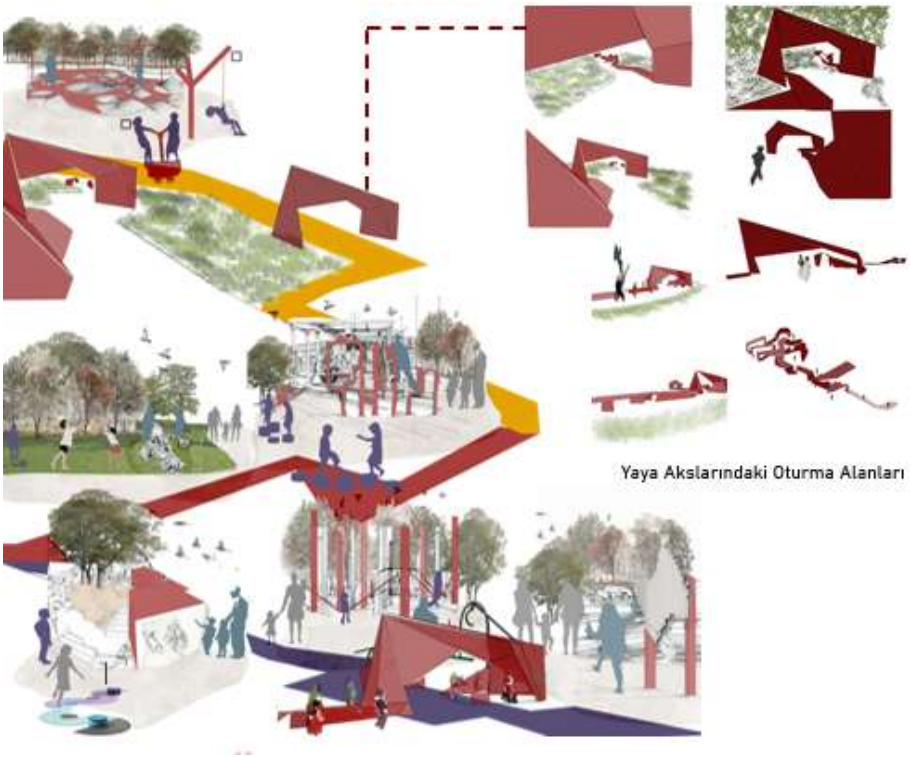

Figure 11. Conceptual spatial scenarios 4

In conclusion, modernism has created a radical transformation in the fields of architecture and urban planning since the beginning of the 20th century, promoting an approach that encourages functionality, simplicity, geometric order, and the use of new construction technologies. In this context, the spatial conception of modernism has produced powerful ideals in the direction of rejecting traditional urban forms and designing a new way of life. Brasília, designed by Lucio Costa and Oscar Niemeyer, holds a special place in both architectural history and cultural heritage as one of the most comprehensive and holistic examples of a modern city where these ideals were implemented. Its inclusion in the UNESCO World Heritage List confirms the city's exemplary nature in embodying modern principles on a large scale (UNESCO, 2023).

However, the modern planning principles applied since Brasília's founding have sparked various debates over time. The city's structure, based on rigid functional divisions, its spatial organization that necessitates car use, and its transportation system that relegates pedestrian movement to a secondary role have been criticized in terms of sustainability and livability. The spatial separation of residential, administrative, commercial, and recreational areas has led to the dispersion of daily functions over long distances and limited social interaction; this has made it particularly difficult for low-income groups to access urban life (Holston, 1989; Ferreira, 2015).

In an environmental context, the construction of Brasília has had significant impacts on the cerrado ecosystem. The clearing of large areas for urbanization has led to the loss of natural vegetation, a decline in biodiversity, and changes in the local water cycle. The artificial creation of Lake Paranoá provided advantages in terms of water management but also led to transformations in ecological processes; the pressure of construction around the lake has been highlighted as a threat in UNESCO reports (UNESCO State of Conservation Reports, 1993–2023).

The limited availability of recreational areas within the city, the loss of spatial experience in large-scale voids, and the lack of small-scale public spaces for everyday life are among the most significant problems of Brasília's modern design today. In this context, the conservation and improvement of conceptual spatial scenarios developed aim to preserve the city's modern heritage while also increasing spatial livability. Strengthening the relationship between Lake Paranoá and the land, designing modular systems adaptable to different uses, and creating pedestrian-oriented recreational areas around the lake are among the prominent approaches. The preference for triangular modules offers a functional solution in terms of both structural strength and flexible spatial arrangements.

The current state of the Superquadra units, which play an important role in the inner neighborhood organization of Brasília, is inadequate in terms of pedestrian movement and child-centered public spaces. The existing vehicle-oriented road system makes it difficult to move between blocks, and the location and design of parks are not suitable for safe use by children. The proposed design approach aims to reorganize public spaces, strengthen pedestrian and bicycle axes, and safely design parent-child interaction areas, particularly by focusing on children's perceptual scale. This approach constitutes an intervention that will reduce the disconnect between the modern urban unit and social life.

The dysfunctionality of the large-scale empty spaces around the Monumental Axis has caused the city's symbolic core to become disconnected from everyday use. Therefore, re-functionalizing the area as a "Cultural Axis" and supporting it with open exhibitions, event areas, child-focused spaces, and designs that increase public use will both enhance the visibility of the heritage and ensure the axis's integration into daily life.

Brasília can be seen as a comprehensive experiment in the urban lifestyle idealized by modernism; however, the social, environmental, and spatial problems that have emerged throughout history make it necessary to reinterpret this ideal in today's conditions. The sustainability of the city's UNESCO World Heritage status will be possible through planning policies that preserve its modern integrity while prioritizing user needs, strengthening ecological sensitivity, and enriching small-scale public spaces. This study has evaluated Brasília's modern heritage value from both theoretical and practical perspectives, revealing that sustainable conservation approaches can open new horizons for modern cities.

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Dokuma Duruş İzinin Nedenleri, Mekanizmaları ve Giderme Yöntemleri: Üretim ve Kalite Perspektifi

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Özet

Dokuma duruş izi, tezgâhın planlı veya plansız duruşları sonrasında kumaş yüzeyinde ortaya çıkan ve çoğunlukla ton farkı veya mekanik deformasyon biçiminde gözlenen bir kalite kusurudur. Bu olgunun, üretim parametreleri, iplik özellikleri, çevresel koşullar ve operatör müdahale süresi gibi birçok değişkenin etkileşimiyle oluştuğu bilinmektedir. Duruş anında çözgü gerilim dengesinde meydana gelen ani değişimler, kumaşın dokusal bütünlüğünü bozarak hem estetik hem de yapısal açıdan kalıcı izlere yol açmaktadır. Literatürde yapılan çalışmalar, duruş izi davranışının yalnızca mekanik faktörlerle sınırlı olmadığını, haşıl kalitesi, terbiye koşulları, çözgü kondisyonlaması ve yeniden başlatma (restart) algoritmalarının da önemli etkiler yarattığını göstermektedir. Bu çalışmada, dokuma duruş izinin oluşum mekanizmaları çok yönlü biçimde ele alınmış; çözgü gerilimi, tezgâh kontrol sistemi, malzeme özellikleri ve çevresel faktörler arasındaki ilişkiler değerlendirilmiştir. Ayrıca, duruş izinin önlenmesine yönelik mekanik, proses temelli ve veri tabanlı modern yaklaşımlar karşılaştırılmıştır. Elde edilen bilgiler, üretim verimliliği ve kalite kontrol süreçlerinin entegrasyonu açısından dokuma işletmelerine yol gösterici niteliktedir.

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Anahtar Kelimeler
Dokuma Duruş Izi,
Çözgü Gerilimi,
Yeniden Başlatma Kontrolü,
Kumaş Kalitesi,
Proses Optimizasyonu

Causes, Mechanisms and Solutions of Loom Stops: A Productıon and Quality Perspective

Abstract

The weaving stop mark is a quality defect that appears on the fabric surface following planned or unplanned loom stoppages, typically manifested as tonal variation or mechanical deformation. This phenomenon results from the interaction of multiple factors such as production parameters, yarn characteristics, environmental conditions, and operator intervention time. Sudden changes in warp tension equilibrium during stoppage disturb the structural integrity of the fabric, leading to permanent marks that affect both its aesthetic and mechanical properties. Previous studies have revealed that stop mark behavior is not solely dependent on mechanical factors but is also influenced by sizing quality, finishing conditions, warp conditioning, and restart algorithms. In this study, the mechanisms of weaving stop mark formation are examined from multiple perspectives, evaluating the interrelations among warp tension, loom control systems, material properties, and environmental conditions. Furthermore, mechanical, process-oriented, and data-driven approaches to prevent stop mark formation are compared. The findings provide valuable insights for integrating production efficiency and quality assurance in modern weaving operations.

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Keywords
Weaving Stop Mark,
Warp Tension,
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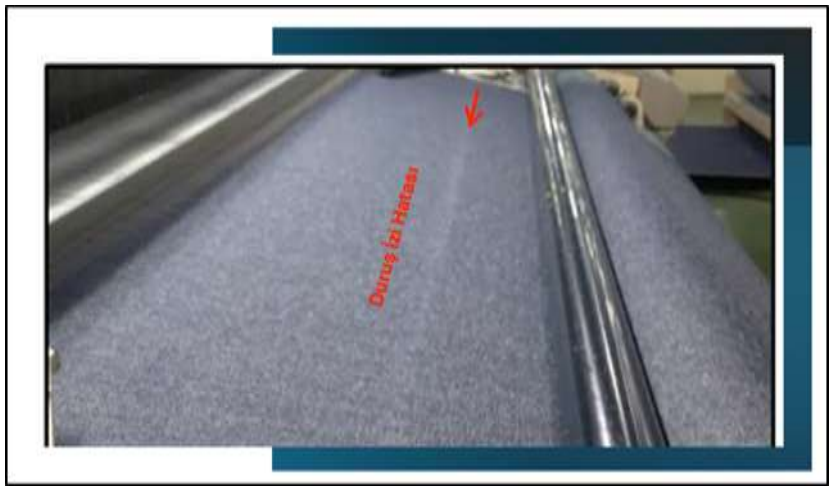
Process Optimization

1. Giriş

Dokuma kumaş üretiminde duruş izi, tezgâhın planlı veya plansız biçimde durması sonucu çözgü sisteminde meydana gelen gerilim dengesizliğine bağlı olarak kumaş yüzeyinde oluşan kalıcı hatalar şeklinde tanımlanmaktadır. Genellikle ton farkı, parlaklık değişimi veya yerel deformasyon biçiminde gözlenen bu izler, kumaşın hem estetik görünümünü hem de yapısal bütünlüğünü olumsuz etkileyerek ürünün sınıfını ve satış değerini düşürmektedir (Şekil 1). Özellikle yüksek kaliteli gömleklik, döşemelik ve teknik kumaşlarda bu kusur, üretim randımanının yanı sıra A sınıfı kalite oranını da doğrudan azaltan kritik bir parametre hâline gelmiştir.



Şekil1. Dokuma kumaşlarda duruş izi hatası

Duruş izinin oluşum süreci, birbirine bağlı çok sayıda mekanik, malzeme, çevresel ve operasyonel faktörün etkileşimiyle ortaya çıkan karmaşık bir olaydır. Tezgâhın ani duruşu sırasında çözgü ipliklerinin bir kısmı gerilimini korurken bir kısmı gevşer; tezgâhın yeniden başlatılması (restart) aşamasında bu iplikler farklı uzama davranışları sergileyerek dokuma alanında lokal yoğunluk farklılıklarına yol açar. Bu durum, kumaş yüzeyinde bant benzeri görsel izlerin oluşmasına neden olur. Duruş izi şiddeti; duruş süresi, tezgâh tipi, haşıl kalitesi, iplik elastikiyeti, çözgü kondisyonlaması, nem-sıcaklık dengesi ve operatör müdahale süresi gibi birçok değişkenle yakından ilişkilidir.

Konuya yönelik ilk sistematik gözlemler, 19. yüzyılın sonlarında Redding (1896) ve Kelmel (1911) tarafından mekanik tezgâhlarda yapılan çalışmalarla başlamıştır. Bu araştırmalar, duruş sonrası motor frenlemesinin çözgü iplikleri üzerinde farklı gerilim dağılımlarına neden olduğunu ve bunun kumaş yüzeyinde şerit biçimli ton farkları oluşturduğunu göstermiştir. Daha sonraki deneysel çalışmalar (örneğin Smith & Jones, 1974; Sönmez, 1998) duruş izi şiddetinin duruş süresiyle logaritmik olarak arttığını, ayrıca haşıl oranı yüksek çözgülerde elastik toparlanmanın daha zayıf gerçekleştiğini ortaya koymuştur. Bu bulgular, çözgü ipliklerinin elastik davranışı ve haşıl kalitesinin duruş izi oluşumundaki belirleyici rolünü açıkça vurgulamaktadır.

Modern üretim sistemlerinde duruş izi problemi, mekanik çözümler ve elektronik kontrol mekanizmalarıyla azaltılmaya çalışılmıştır. Picanol ve Toyota (2005) teknik raporlarında, elektronik kontrollü “soft start” sistemlerinin duruş izi görünürlüğünü %70’e kadar düşürdüğü, servo motor tabanlı frenleme ve hızlanma algoritmalarının çözgü gerilimini stabilize ettiği rapor edilmiştir. Benzer biçimde Dornier (2009), geliştirdiği çözgü gerilim kompanzasyon sistemlerinin ani duruşlarda bile ΔT (tension variation) değerini 1,5 N’un

altına düşürebildiğini belirtmiştir. Bu gelişmeler, duruş izinin yalnızca fiziksel bir kusur değil, aynı zamanda mekatronik sistem tasarımında da kalite göstergesi olarak ele alınması gerektiğini göstermektedir.

Son yıllarda araştırmalar, duruş izi davranışını sensör tabanlı ölçüm, görüntü işleme ve veri analitiği teknikleriyle incelemeye yönelmiştir. Liu ve ark. (2018), yüksek çözünürlüklü kamera sistemleriyle duruş izlerinin parlaklık farklarını ΔL* parametresiyle nicelleştirerek görsel hataların sınıflandırılmasına olanak tanımıştır. Acar ve Demir (2021) ise yapay sinir ağları (ANN) kullanarak duruş tipi (atkı kopuşu, çözgü kopuşu, enerji kesintisi) ile iz yoğunluğu arasındaki ilişkiyi tahmin etmiş; sonuçta, üretim hattı verilerinden iz şiddetinin öngörülebileceğini göstermiştir. Bu yaklaşım, klasik kontrol parametrelerinin ötesine geçerek veri temelli kalite tahmin modellerinin geliştirilmesini sağlamıştır.

Ayrıca Kaur ve Singh (2022) tarafından geliştirilen Random Forest modeli, çözgü gerilimi, ortam nemi, tezgâh hızı ve operatör müdahale süresi gibi değişkenleri kullanarak duruş izi oluşma olasılığını %93 doğrulukla tahmin etmiştir. Bu tür yapay zekâ tabanlı yaklaşımlar, duruş izi oluşmadan önce sistemin erken uyarı verebildiği akıllı dokuma uygulamalarının temelini oluşturmuştur.

Literatürdeki bu gelişmelere rağmen, duruş izi probleminin hâlen çok faktörlü ve tamamen çözümlenmemiş bir konu olduğu görülmektedir. Çoğu çalışma yalnızca belirli parametrelere odaklanmakta, çözgü gerilimi, iplik özellikleri, ortam koşulları ve yeniden başlatma algoritmalarının bir arada değerlendirildiği entegratif modeller oldukça sınırlı kalmaktadır. Bu durum, duruş izinin sadece mekanik bir arıza değil, üretim–kalite etkileşimini kapsayan sistemik bir problem olarak ele alınması gerektiğini göstermektedir.

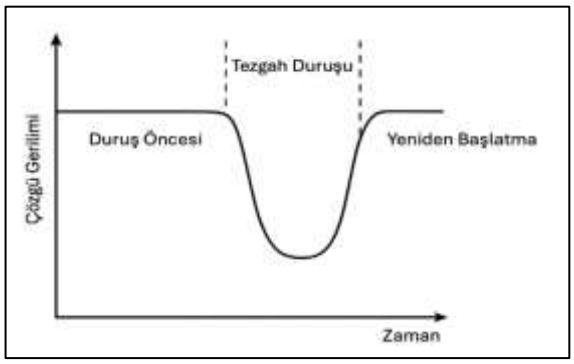
Bu bağlamda, bu çalışmada dokuma duruş izinin oluşum mekanizmaları, nedenleri ve giderme yöntemleri farklı açılardan değerlendirilmiştir. Çözgü gerilimi, iplik yapısı, tezgâh kontrolü, ortam koşulları ve operatör etkisi arasındaki ilişkiler hem klasik literatür hem de modern veri tabanlı yaklaşımlar ışığında incelenmiştir. Böylelikle, duruş izinin azaltılmasına yönelik mekanik, proses temelli ve yapay zekâ destekli stratejilerin üretim ve kalite yönetimi açısından bütüncül bir bakışla değerlendirilmesi amaçlanmıştır.

2. Duruş İzi Oluşum Mekanizmaları

Dokuma duruş izi, tek bir kaynaktan değil; üretim süreci boyunca birbirine bağlı mekanik, malzeme, çevresel ve operasyonel faktörlerin etkileşimiyle ortaya çıkan çok boyutlu bir fenomendir. Bu nedenle iz oluşum mekanizmalarının incelenmesi, yalnızca tezgâh duruş anına odaklanmak yerine, iplik hazırlığı, tezgâh kontrol sistemi ve yeniden başlatma davranışının bütüncül olarak değerlendirilmesini gerektirir.

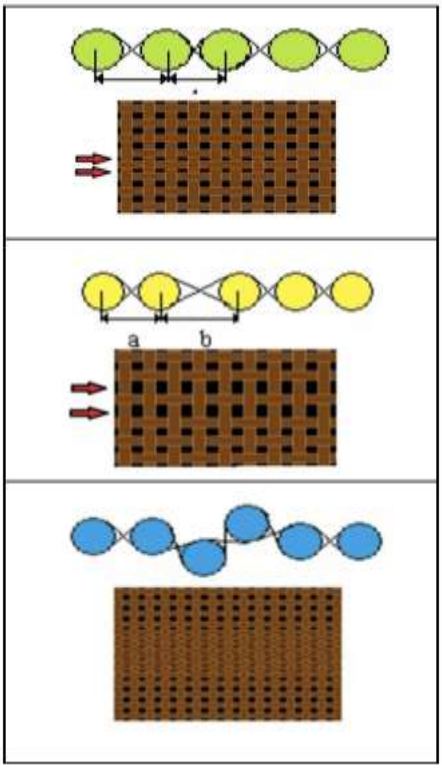
2.1. Mekanik faktörler

Duruş izinin en belirgin nedenlerinden biri, tezgâhın ani duruşu veya yeniden başlatma aşamasında çözgü geriliminde meydana gelen ani değişimlerdir. Tezgâh motoru durduğunda çözgü kütlesi moment etkisiyle gerilimini bir süre korur; ancak frenleme kuvveti iplikler arasında eşit dağılmadığında çözgü tabakasının bir kısmı gevşer, diğer kısmı ise aşırı gerilir. Bu dengesizlik, yeniden başlatma sırasında çözgü ipliklerinin farklı uzama davranışı göstermesine yol açar. Sonuçta, kumaş yüzeyinde atkı yönünde (kumaş enine) bantlaşma/ton farkı biçiminde duruş izleri oluşur. Şekil 2 çözgü ipliklerinin duruş öncesi ve sonrası geriliminin zamana bağlı değişimini vermektedir. Bu gerilim farkı ile oluşan kumaştaki duruş izi görüntüleri de Şekil 3’ de verilmiştir.



Şekil 2. Duruş öncesi, tezgâh duruşu ve yeniden başlatma (restart) aşamalarında çözgü gerilimi değişimi

Duruş süresi uzadıkça ipliklerin iç gerilimi azalır ve çözgü tabakası kısmen rahatlar; bu da iz şiddetinin duruş süresiyle logaritmik biçimde artmasına neden olur (Smith and Jones, 1974). Ayrıca, farklı tezgâh tiplerinin (mekanik, hava jetli, rapier) frenleme sistemleri arasındaki farklar, duruş izinin biçimini ve yoğunluğunu değiştirmektedir. Modern tezgâhlarda kullanılan servo motor kontrollü "soft start" sistemleri, yeniden başlatma aşamasında ivmelenmeyi kademeli hâle getirerek çözgü gerilimi dalgalanmalarını %60–70 oranında azaltmaktadır (Toyota, 2005; Dornier, 2009).



Şekil 3. Duruş sonrası kumaşta atkı ipliklerinin farklı konumlanma tipleri: (üst) sık atkı aralığı, (orta) gevşek atkı aralığı, (alt) atkı ipliklerinin üst üste binmesiyle oluşan tepe (ridge) bölgesi (TextileLearner, 2023)

Çözgü gerilim kompanzatörleri ve elektronik fren kontrol sistemleri, özellikle atkı kopuşu sonrası kısa duruşlarda gerilim farklarını dengeleyerek iz oluşumunu büyük ölçüde

sınırlamaktadır. Ancak, ani enerji kesintisi veya çoklu kopuş gibi uzun duruşlarda, bu sistemlerin etkinliği kısmen azalmaktadır. Bu durum, mekanik kontrol sistemlerinin yalnızca kısa süreli duruşlarda yeterli olduğu, uzun duruşların ise proses temelli önlemler gerektirdiği sonucunu doğurmuştur.

2.2. Malzeme kaynaklı faktörler

İplik yapısı, duruş izi oluşumunda belirleyici rol oynayan parametrelerden biridir. Büküm yönü, büküm miktarı, iplik elastikiyeti, mukavemet ve sürtünme katsayısı, çözgü gerilimi değişimlerine verilen tepkiyi doğrudan etkiler. Büküm miktarı yüksek veya düşük olan iplikler, duruş sırasında farklı uzama oranlarına sahip olduğundan yeniden başlatma sonrası kumaşta yerel sıklık farkları oluşur.

Ayrıca, haşıl kompozisyonu ve kalitesi, ipliklerin gerilim altındaki davranışını önemli ölçüde etkiler. Haşıl çözeltisinde kullanılan PVA, nişasta, antistatik ve yumuşatıcı katkılar, ipliğin yüzey sürtünmesini ve esneme kapasitesini belirler. Düşük kaliteli haşıl, iplik yüzeyinde heterojen bir film tabakası oluşturarak çözgü boyunca farklı sürtünme değerleri yaratır; bu da duruş izi oluşumuna katkı sağlar.

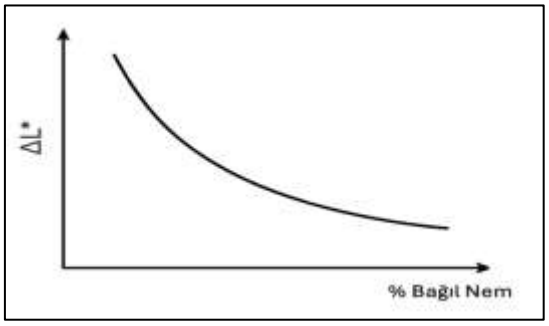
Haşıl kalitesi, dokuma sonrası terbiye koşulları ve çözgü kondisyonlaması, dokuma sırasında iplik sürtünme katsayısını ve gerilim dengesini doğrudan etkileyerek duruş izi oluşumuna katkı sağlar. Nitekim Sönmez (1998), haşıl oranı yüksek çözgülerde elastik toparlanmanın daha zayıf olduğunu ve bu durumun iz şiddetini artırdığını rapor etmiştir.

Buna ek olarak, farklı iplik tiplerinin (örneğin kompakt, sirospun, open-end) elastikiyet farkları da iz davranışını değiştirmektedir. Kompakt ipliklerin daha düşük tüylülük ve daha homojen yüzey yapısı, gerilim dengesini koruma eğilimini artırırken; open-end ipliklerde gevşeme eğilimi daha fazladır. Bu nedenle iplik yapısı ile duruş izi şiddeti arasında korelasyon olduğu kabul edilmektedir.

2.3. Çevresel Faktörler

Duruş izi oluşumuna katkı sağlayan bir diğer etken, ortam sıcaklığı ve bağıl nemdir. Dokuma salonundaki düşük nem oranı, çözgü ipliklerinin yüzey sürtünmesini artırır; bu durum hem iplik kopuş sıklığını hem de duruş izinin belirginliğini yükseltir (Teli & Valia, 2019). Yüksek nem ise ipliklerin uzama kabiliyetini artırarak çözgü geriliminin kısmen dengelenmesini sağlar (Acar, 2015). Bu nedenle sabit iklimlendirme koşulları (RH %60–65, 20–25 °C) duruş izi riskini azaltan önemli bir parametredir (ASTM D1776-20, 2020).

Ortam nemi yalnızca iplik gerilimini değil, aynı zamanda kumaş yüzeyindeki optik farklılıkları da etkiler. Bu fark, renk ölçümünde kullanılan CIE L*a*b* sistemindeki **ΔL*** parametresiyle ifade edilir ve yüzeyin açıklık–koyuluk farkını gösterir. Bağıl nem arttıkça ΔL* değeri azalmakta, yani duruş izi görünürlüğü azalmaktadır (Şekil 4).



Şekil 4. Ortam bağıl nemi (RH%) ile kumaş yüzey parlaklık farkı (ΔL*) arasındaki ilişki

Ayrıca, uzun süreli üretimlerde tezgâhın bulunduğu bölgedeki sıcaklık dalgalanmaları, metal aksam ve iplik uzama farklarını etkileyerek gerilim dengesinde periyodik salınımlar yaratabilir (Teli and Valia, 2019; ASTM D1776-20, 2020). Bu nedenle modern işletmelerde çevresel veriler, otomatik nem–sıcaklık kontrol sistemleri ile sürekli izlenmekte ve dokuma parametreleri buna göre ayarlanmaktadır (Acar, 2015).

2.4. Operasyonel faktörler

Operatör müdahale süresi, duruş izinin görünürlük derecesini doğrudan etkileyen insana bağlı bir değişkendir. Duruş sonrası tezgâhın yeniden çalıştırılması için geçen süre uzadıkça, çözgü ipliklerinin elastik geri dönüşü azalır ve iz şiddeti artar (Redding, 1896; Smith and Jones, 1974). Bu durum, özellikle manuel yeniden başlatma yapılan klasik tezgâhlarda daha belirgindir (Sönmez, 1998). Ayrıca, operatörün yeniden başlatma öncesinde çözgü gerginliğini elle düzeltmesi veya atkı ipliğini elle yerleştirmesi gibi müdahaleler, tezgâhlar arasında kalite farklarına neden olabilir. Eğitimli operatörlerin doğru müdahale zamanlaması, duruş izi oluşum sıklığını önemli ölçüde azaltmaktadır (Acar, 2015). Bu nedenle, işletmelerde operatör performansının izlenmesi ve duruş kayıtlarının istatistiksel olarak değerlendirilmesi (örneğin λ–μ oranı, duruş başına ortalama süre) kalite yönetiminde önemli bir göstergedir (Montgomery, 2012; Acar and Demir, 2021).

Yeni nesil işletmelerde, duruş ve yeniden başlatma davranışlarını analiz eden veri toplama sistemleri (Loom Data Monitoring Systems), operatör müdahale sürelerini kayıt altına alarak üretim planlaması ve bakım stratejilerine veri sağlamaktadır (Picanol, 2005; Kaur and Singh, 2022). Böylece, insan kaynaklı hatalar sistematik biçimde analiz edilip öngörücü bakım ve eğitim programlarıyla giderilebilmektedir (Acar, 2015; Dornier, 2009).

3. Duruş İzinin Tespiti ve Analiz Yöntemleri

Dokuma duruş izinin belirlenmesi, yalnızca görsel bir değerlendirme süreci değil; aynı zamanda kumaşın yapısal, optik ve mekanik özelliklerindeki farklılıkların analitik olarak incelenmesini gerektirir. Bu nedenle duruş izi tespitinde kullanılan yöntemler, gözle muayene tekniklerinden görüntü işleme tabanlı sistemlere kadar uzanan geniş bir yelpazede sınıflandırılabilir. Son yıllarda, özellikle kalite kontrolün otomasyonla bütünleşmesi sayesinde, duruş izi tespitinde nicel ölçüm yöntemlerinin önemi artmıştır.

3.1. Görsel ve optik değerlendirme yöntemleri

Duruş izinin ilk ve en yaygın tespit yöntemi, kumaş yüzeyinde oluşan renk ve parlaklık farklarının görsel kontrolüdür. Üretim sonrası muayene masalarında yapılan bu kontrol, genellikle 1000–2000 lux aydınlatma koşullarında gerçekleştirilir. Ancak, operatörün göz yorgunluğu, ışık yönü ve kumaşın rengi gibi değişkenler sonucu, görsel değerlendirmelerde öznel hatalar oluşabilmektedir.

Bu nedenle, modern sistemlerde görsel kontrolün yerine optik spektrofotometrik ölçümler kullanılmaktadır. Duruş izi bölgeleri ile normal kumaş yüzeyi arasındaki renk farkı, CIE Lab renk uzayında ΔE* parametresiyle nicelleştirilir. ΔE değeri genellikle 0,8–1,0'in üzerinde olduğunda insan gözü tarafından fark edilir kabul edilir. Liu ve ark. (2018), yüksek çözünürlüklü kamera sistemleri kullanarak duruş izi bölgelerinde ΔL* farkının 3,5'in üzerinde olması hâlinde izlerin görsel olarak belirginleştiğini göstermiştir. (CIE, 2004; HunterLab, 2010) Ayrıca, yansıma oranı (reflectance) ve yüzey parlaklığı ölçümleri, iz bölgelerindeki yüzey topografyasındaki değişimi belirlemekte kullanılır. Özellikle çözgü yönündeki mikroskobik seviye deformasyonlar, ışığın yansıma açısını değiştirerek optik parlaklık farkı yaratır. Bu fark, glossmetre veya reflektometre cihazlarıyla ölçülerek sayısal olarak ifade edilir.

3.2. Mekanik ve fiziksel analiz yöntemleri

Duruş izinin yapısal etkilerini değerlendirmek amacıyla çeşitli mekanik test yöntemleri kullanılmaktadır. Bu testler, duruş izi bölgesi ile normal kumaş yüzeyinin karşılaştırılması esasına dayanır.

- FAST (Fabric Assurance by Simple Testing) sisteminde yapılan FAST–1 (kalınlık), FAST–2 (eğilme sertliği) ve FAST–3 (gerilim altında uzama) testleri, duruş izi bölgesinde lif ve iplik deformasyonlarını ortaya koymakta etkilidir. Duruş izi bölgesinde genellikle eğilme sertliği ve kalınlık değerleri artış göstermekte, bu da kumaşın tuşe ve drape (dökümlülük) özelliklerinde fark yaratmaktadır. (Kawabata, 1980; FAST Handbook, 2002)

- KES–F (Kawabata Evaluation System for Fabrics) testlerinde ise yüzey sürtünmesi (MIU) ve gerilme enerjisi (WT) parametreleri incelenir. Duruş izi bölgesinde bu değerlerin artışı, ipliklerin uzama davranışında kalıcı deformasyona işaret eder. (Kawabata, 1980; FAST Handbook, 2002)

- Çekme dayanımı (ISO 13934) ve yırtılma dayanımı (ISO 13937) testleri, iz bölgesinde mikro düzeyde lif kopmalarını gösterebilir. Bu testler, duruş izinin yalnızca görsel değişim değil, aynı zamanda mekanik bir zayıflama oluşturduğunu kanıtlar niteliktedir.

Bazı araştırmacılar, duruş izi bölgesinde atkı sıklığı ve çözgü sıklığı değerlerinin değişimini ölçmek için optik sayım sistemleri (Pick Density Analyzer) kullanmış; iz bölgesinde sıklık artışının genellikle %3–5 arasında olduğunu bildirmiştir. Bu fark, dokuma sırasında iplik uzama farklarından kaynaklanır ve kumaşın yüzey geometrisinde mikroskobik bir bozulmaya yol açar.

3.3. Sensör tabanlı gerilim izleme sistemleri

Duruş izi mekanizmasının anlaşılmasında en önemli parametrelerden biri çözgü gerilim değişimidir. Bu nedenle modern tezgâhlarda load cell veya piezoelektrik sensörler aracılığıyla çözgü gerilimi anlık olarak izlenmektedir.

Bu sistemler, duruş ve yeniden başlatma anında gerilim dalgalanmalarını kaydederek, duruş izi oluşma potansiyelini önceden tahmin etmeye olanak tanır. Örneğin Picanol (2005) tarafından geliştirilen “Tension Equalizer” (Gerilim Eşitleyici) modülü, çözgü gerilimini milisaniye düzeyinde izleyerek yeniden başlatma sırasında oluşan dengesizlikleri minimize etmektedir. (Toyota, 2005; Picanol, 2005)

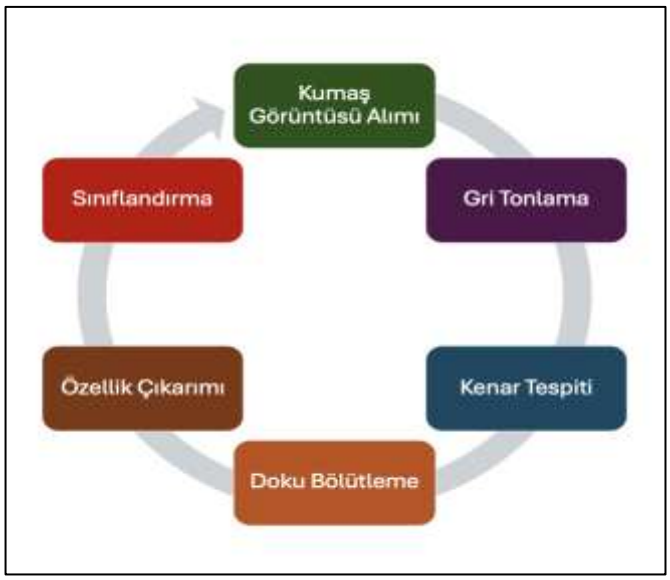
Ayrıca, Liu ve ark. (2020) duruş anında kaydedilen gerilim verilerini kullanarak gerilim farkı-zaman (ΔT–t) eğrileri oluşturmuş ve gerilim değişiminin 2,0 N eşiğini aştığı durumda iz oluşumunun kaçınılmaz hâle geldiğini belirtmiştir. Bu bulgu, duruş izi analizinde gerilim eşik değerlerinin belirlenmesinin önemini vurgulamaktadır.

Sensör tabanlı sistemlerin avantajı, yalnızca iz tespiti değil, aynı zamanda proaktif kontrol imkânı sunmasıdır. Gerilim sensörlerinden elde edilen veriler, tezgâh kontrol yazılımlarına aktarılır ve sistem, belirli bir eşik aşıldığında otomatik yeniden başlatma yavaşlatması veya kompanzasyon moduna geçiş sağlayabilir. Bu sayede duruş izi oluşumu henüz kumaş yüzeyine yansımadan önlenebilir.

3.4. Görüntü işleme ve yapay zekâ tabanlı yaklaşımlar

Son dönemde, dokuma yüzey hatalarının otomatik tanımlanmasında görüntü işleme teknikleri ve yapay zekâ algoritmaları kullanılmaktadır. Duruş izleri, düzenli bir yönelime sahip oldukları için klasik kumaş hatalarına (atkı atlama, çift atma, iplik kopuşu vb.) kıyasla daha kolay sınıflandırılabilir.

Liu ve ark. (2018), gri tonlu görüntüler üzerinde edge detection (kenar tespiti) ve texture segmentation (doku bölütleme) yöntemlerini kullanarak duruş izi bölgelerini %95 doğrulukla ayırt etmiştir. Daha sonra bu veriler, yapay sinir ağı (ANN) ve Destek Vektör Makineleri (SVM) modellerine beslenerek hata türlerinin sınıflandırılması sağlanmıştır (Acar and Demir, 2021). Şekil 5'te duruş izinin algılanmasında kullanılan görüntü işleme adımları görülmektedir.



Şekil 5. Duruş izi tespitinde kullanılan görüntü işleme adımlarının döngüsel akış diyagramı

Acar ve Demir (2021) ise üretim verilerini kullanarak duruş tipi–iz yoğunluğu korelasyonu oluşturmuş ve iz oluşma olasılığını öngörmek için çok katmanlı bir ANN modeli geliştirmiştir. Kaur ve Singh (2022)'nin Random Forest tabanlı sistemi, duruş izi oluşumunu %93 doğrulukla tahmin ederek üretim hattını önceden uyaran bir yapay zekâ altyapısı geliştirmiştir. (Kaur and Singh, 2022)

Bu çalışmalar, duruş izi analizinde geleceğin yönünü göstermektedir: veri temelli, kendi kendini öğrenen ve erken uyarı üretebilen sistemler. Böylece dokuma prosesinde hata oluşmadan önce müdahale edilerek hem kalite hem de randıman artırılabilmektedir.

4. Duruş izinin giderilmesi ve önlenmesi yöntemleri

Duruş izi problemi, dokuma sürecinde yalnızca estetik bir kalite sorunu değil, aynı zamanda üretim verimliliği ve ekonomik kayıplar açısından da kritik bir konudur. Bu nedenle, duruş izinin giderilmesi ve önlenmesine yönelik yöntemler; mekanik sistem geliştirmeleri, proses optimizasyonu, operatör temelli uygulamalar ve veri tabanlı yapay zekâ yaklaşımları şeklinde dört ana başlıkta ele alınmaktadır. Amaç, duruş sonrası oluşan gerilim dengesizliğini en aza indirmek, iplik deformasyonunu kontrol altına almak ve yeniden başlatma sürecini kontrollü hâle getirerek kumaş yüzeyinde iz oluşumunu engellemektir.

4.1. Mekanik ve kontrol tabanlı çözümler

Duruş izinin fiziksel temeli, duruş ve yeniden başlatma anında çözgü gerilimindeki ani değişimlere dayandığından, öncelikli çözüm alanı mekanik kontrol sistemlerinin iyileştirilmesidir.

Modern dokuma tezgâhlarında kullanılan servo motor kontrollü "soft start–soft stop" mekanizmaları, tezgâhın hızını ve ivmelenmesini kademeli olarak değiştirerek çözgü

ipliklerinin eş zamanlı gerilimini sağlar. Toyota (2005) ve Picanol (2005) tarafından geliştirilen sistemlerde, duruş anındaki frenleme kuvveti elektronik olarak dengelenmekte; yeniden başlatma sırasında hız artışı milisaniye düzeyinde kontrol edilerek gerilim sıçramaları önlenmektedir.

Ayrıca çözgü gerilim kompanzatörleri (warp tension compensator) ve otomatik frenleme sistemleri, duruş süresi boyunca çözgü kütlesinin ağırlığından kaynaklanan gerilim değişimini düzenleyerek iz riskini azaltır. Dornier (2009) tarafından rapor edilen çalışmalarda, kompanzatörlü sistemlerde ΔT (tansiyon varyasyonu) değerinin 1,5 N'un altına düşürülmesiyle iz oluşumunun gözle görülür biçimde azaldığı bildirilmiştir.

Bazı üreticiler, özellikle yüksek hızlı tezgâhlarda aktif yeniden başlatma kontrol modülleri (Active Restart Control – ARC) kullanarak, tezgâhın durduğu andaki çözgü açısı ve atkı konumuna göre yeniden başlatma ivmesini otomatik olarak ayarlamaktadır. Bu sistemler, duruş izinin yalnızca azaltılmasını değil, önceden önlenmesini mümkün kılmaktadır.

4.2. Proses temelli optimizasyon yaklaşımları

Duruş izinin önlenmesinde yalnızca tezgâh kontrolü yeterli değildir; iplik hazırlık, haşıl kalitesi, ortam koşulları ve dokuma sonrası terbiye işlemleri de doğrudan etkilidir. (Teli and Valia, 2019)

Haşıl kalitesi, iplik yüzey sürtünmesi ve elastikiyet üzerinde belirleyici bir etkendir. Homojen haşıl filmi oluşturmayan reçeteler, iplik boyunca farklı sürtünme bölgeleri yaratır ve yeniden başlatma sırasında iplik uzamasını düzensizleştirir. Bu nedenle haşıl kompozisyonunun standardizasyonu, duruş izi önleme çalışmalarında temel bir adımdır. (Teli and Valia, 2019)

Benzer biçimde, çözgü kondisyonlaması (nemlendirme, sıcaklık dengesi) ipliklerin gerilim altındaki davranışını doğrudan etkiler. Ortam neminin %60–65, sıcaklığın ise 20–25 °C aralığında tutulması, çözgü ipliklerinin uzama davranışını homojenleştirir. Haşıl kalitesi, terbiye koşulları ve çözgü kondisyonlaması birlikte ele alındığında, iplik sürtünme katsayısının kontrol altına alınması ve dolayısıyla duruş izi oluşumunun minimize edilmesi sağlanabilir. (Teli and Valia, 2019)

Ayrıca, atkı ipliği giriş zamanlamasının optimize edilmesi, yeniden başlatma sırasında atkı yoğunluğunda oluşan yerel artışların önüne geçer. Bu amaçla, modern tezgâhlarda elektronik atkı zamanlama sensörleri kullanılmakta ve yeniden başlatma sırasında atkı atımının faz farkı ±0,5° sınırında tutulmaktadır.

Dokuma sonrası terbiye aşamasında uygulanan ısı fikse, sanfor veya kurutma prosesleri de duruş izi görünürlüğünü değiştirebilir. Uygun gerilim altında yapılan termomekanik işlemler, iz bölgesindeki lif deformasyonlarını kısmen düzeltebilir. Ancak yüksek sıcaklıkta yapılan agresif kurutmalar, iz farkını belirginleştirebilir. Bu nedenle finishing aşaması, iz giderme açısından dengeleyici değil, destekleyici bir rol üstlenmektedir.

4.3. Operasyonel ve eğitimsel önlemler

Duruş izinin görünürlüğü, büyük ölçüde operatör müdahale süresi ve yeniden başlatma prosedürüne uyum ile ilişkilidir. Duruş sonrası tezgâhın yeniden çalıştırılmasında geçen süre uzadıkça, çözgü ipliklerinin iç gerilimi azalır ve iz belirginleşir. Bu nedenle, standart yeniden başlatma protokolleri geliştirilerek tüm operatörlerin aynı prosedürü uygulaması sağlanmalıdır.

Operatör eğitimleri kapsamında; duruş sonrası çözgü kontrolü, iplik gerginliği dengesi ve atkı pozisyonu denetimi gibi temel adımlar öğretilmeli, manuel müdahale hataları en aza

indirilmelidir. Duruş süresi kayıtlarının analizi, işletmelerin operatör bazlı performansını ölçerek süreç iyileştirmelerine veri sağlar.

Ayrıca, duruş izi eğilimlerini izlemek için istatistiksel proses kontrolü (İPK) tekniklerinden yararlanılabilir. Duruş sıklığı (λ), müdahale süresi (μ) ve iz şiddeti parametreleri kullanılarak oluşturulan kontrol grafiklerinde sapma noktaları belirlenebilir. Bu sayede, duruş izi probleminin yalnızca kalite değil, aynı zamanda verimlilik göstergesi olarak da izlenmesi mümkün olur.

4.4. Veri tabanlı ve yapay zekâ destekli sistemler

Endüstri 4.0 uygulamalarıyla birlikte dokuma prosesinde veri temelli kalite kontrol anlayışı yaygınlaşmıştır. Gerilim sensörleri, hız ölçerler, ortam sensörleri ve görüntü işleme kameralarından gelen veriler, yapay zekâ algoritmalarıyla bütünleştirilerek erken uyarı sistemleri oluşturulmaktadır.

Acar ve Demir (2021), dokuma tezgâhlarından elde edilen çözgü gerilimi, tezgâh hızı ve duruş süresi verilerini kullanarak yapay sinir ağı (ANN) modeliyle duruş tipi ve iz şiddetini tahmin etmiştir. Kaur ve Singh (2022) ise Random Forest algoritmasıyla duruş izi oluşum olasılığını %93 doğrulukla öngörmüştür. Bu çalışmalar, yapay zekâ destekli sistemlerin yalnızca iz tespiti değil, aynı zamanda proaktif önleme potansiyeline sahip olduğunu göstermektedir. (Acar and Demir, 2021; Kaur and Singh, 2022)

Yeni nesil dokuma hatlarında bu veriler, tezgâh kontrol yazılımına entegre edilerek gerilim eşikleri aşıldığında otomatik hız azaltma veya yeniden başlatma geciktirme fonksiyonlarını devreye sokmaktadır. Böylece sistem, duruş izi oluşmadan önce kendini koruma moduna alarak üretim kalitesini sürdürmektedir.

Veri analitiği, yalnızca anlık kontrol değil, aynı zamanda öngörücü bakım (predictive maintenance) yaklaşımına da olanak sağlar. Duruş izine neden olan gerilim sapmaları, tekrarlayan frekansta görüldüğünde sistem bunu olası ekipman hatası olarak algılayabilir ve bakım ekibini uyarabilir. Böylelikle dokuma süreci yalnızca kalite açısından değil, süreklilik ve bakım verimliliği açısından da optimize edilir.

5. Sonuç

Dokuma duruş izi, yalnızca üretim sürecinde ortaya çıkan görsel bir kusur değil; aynı zamanda çözgü gerilimi, iplik özellikleri, ortam koşulları ve operatör davranışı arasındaki karmaşık etkileşimlerin sonucu olan çok boyutlu bir olgudur. Yapılan çalışmalar, duruş izinin mekanik, malzeme, çevresel ve operasyonel faktörlerin ortak etkisiyle geliştiğini; bu etkileşim doğru biçimde yönetilmediğinde iz oluşumunun kaçınılmaz hâle geldiğini göstermektedir.

Mekanik sistemlerdeki gelişmeler, özellikle servo motor kontrollü “soft start–soft stop” mekanizmaları, çözgü gerilim kompanzatörleri ve aktif yeniden başlatma kontrol sistemleri, duruş sonrası gerilim dengesizliğini önemli ölçüde azaltmıştır. Ancak bu teknolojik ilerlemeler, sorunu tamamen ortadan kaldırmakta yeterli olamamıştır; zira duruş izinin yapısal temeli yalnızca makine kaynaklı değildir. İplik yapısı, haşıl kompozisyonu, çözgü kondisyonlaması ve ortam nem dengesi gibi proses parametreleri de iz şiddetini doğrudan etkileyen unsurlardır. Bu nedenle duruş iziyle mücadelede mekanik sistemlerin yanı sıra proses temelli optimizasyon stratejileri de eşzamanlı olarak uygulanmalıdır.

Öte yandan, duruş izinin görünürlüğü ve sıklığı, büyük ölçüde operatör müdahale süresi ve uygulama standardı ile ilişkilidir. Duruş sonrası tezgâhın yeniden devreye alınmasında geçen sürenin uzaması, çözgü ipliklerinin iç gerilimini azaltarak iz şiddetini artırır. Bu nedenle işletmelerde standart yeniden başlatma protokollerinin uygulanması, düzenli

eğitimlerle desteklenmiş operatör farkındalığı ve performans izlemesi büyük önem taşımaktadır.

Son yıllarda dokuma işletmelerinde duruş izi tespitine yönelik yöntemler, klasik görsel muayeneden optik sensör, görüntü işleme ve yapay zekâ tabanlı sistemlere doğru evrilmiştir. Spektrofotometrik ölçümlerle belirlenen ΔE ve ΔL* farkları, kumaş yüzeyindeki mikroskobik değişimleri nicel biçimde gösterebilmekte; sensör tabanlı sistemler ise çözgü gerilimindeki dalgalanmaları anlık olarak izleyebilmektedir. Bu gelişmeler, hatanın yalnızca tespiti değil, oluşmadan önce öngörülmesi için de yeni olanaklar sunmaktadır.

Yapay zekâ tabanlı yaklaşımlar (ANN, SVM, Random Forest vb.), duruş tipi, gerilim, nem, tezgâh hızı ve müdahale süresi gibi çoklu değişkenleri işleyerek duruş izi olasılığını yüksek doğrulukla tahmin edebilmektedir. Bu modellerin dokuma makinelerine entegre edilmesiyle, sistem kritik eşikler aşıldığında otomatik hız azaltma veya yeniden başlatma geciktirme fonksiyonlarını devreye sokarak duruş izini daha oluşmadan önleyebilmektedir.

Sonuç olarak, duruş izinin giderilmesi tek bir çözüm alanına indirgenemeyecek kadar karmaşık bir süreçtir. Mekanik kontrol sistemleri ani gerilim değişimlerini sınırlarken, proses temelli yaklaşımlar iplik davranışını dengeler; operatör eğitimi insan faktörünü standartlaştırır. Tüm bu bileşenlerin üzerinde, veri temelli süreç izleme ve yapay zekâ destekli analitik yaklaşımlar, iz oluşumunu hem öngörebilen hem de önleyebilen yeni bir kalite yönetimi paradigmasını temsil etmektedir.

Gelecekte dokuma işletmelerinde duruş iziyle mücadele, akıllı tezgâh sistemleri, gerçek zamanlı veri izleme, öğrenen algoritmalar ve koşul kontrollü üretim stratejileri ile bütünleşik bir yapı kazanacaktır. Böylece hem kalite kontrol süreçleri hızlanacak hem üretim kayıpları minimize edilerek sürdürülebilir bir verimlilik modeli oluşturulacaktır.

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Applications of Artificial Intelligence and Remote Sensing in Environmental and Agricultural Engineering: A Comprehensive Review

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Abstract
Artificial Intelligence (AI) and remote sensing technologies have transformed the landscape of environmental and agricultural engineering. These technologies enable the monitoring, analysis, and prediction of complex natural processes at multiple spatial and temporal scales. This review summarizes current advances in the integration of AI algorithms and remote sensing data for precision agriculture, environmental monitoring, and resource management. Emphasis is placed on the use of machine learning (ML) and deep learning (DL) models for crop yield prediction, soil salinity mapping, water resource optimization, and climate impact assessment. Challenges related to data quality, computational cost, and model generalization are discussed. Finally, the paper highlights future directions for AI-driven sustainable engineering applications.

Review Article

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Remote Sensing,
Environmental Monitoring,
Sustainable Engineering

1. Introduction

In recent decades, global challenges such as climate change, population growth, and resource scarcity have driven the demand for innovative solutions in environmental and agricultural engineering. Artificial Intelligence (AI) and remote sensing (RS) have emerged as key technologies enabling data-driven decision-making in complex natural systems (Wang et al., 2022; Ma et al., 2023). The integration of these tools allows for the efficient monitoring of ecosystems, the optimization of irrigation and fertilization practices, and the prediction of crop yields under variable climatic conditions (Rowley et al., 2023).

AI complements remote sensing by offering advanced computational approaches for analyzing large and complex datasets. Machine learning (ML) and deep learning (DL) algorithms can identify hidden patterns, make predictions, and automate feature extraction from spectral imagery with remarkable accuracy (Kamilaris and Prenafeta-Boldú, 2018). Recent research has demonstrated how convolutional neural networks (CNNs) and random forest models can accurately classify crop types, estimate biomass, and detect stress factors such as nutrient deficiency or disease (Espinel et al., 2024). Similarly, AI-driven models are increasingly used in environmental monitoring to predict soil erosion, flood risks, and water quality variations (Rana et al., 2023).

The convergence of AI and RS technologies represents a paradigm shift toward precision and sustainability in resource management. These tools enable real-time monitoring and forecasting, allowing decision-makers to respond proactively to environmental challenges. Moreover, their integration supports the achievement of several United Nations Sustainable Development Goals (SDGs), including food security, clean water management, and climate resilience (FAO, 2022).

The objective of this review is to provide a comprehensive overview of recent advances in the use of AI and remote sensing for sustainable environmental and agricultural management, emphasizing their technical applications, challenges, and future perspectives. Agricultural and environmental systems are inherently dynamic and multifactorial, influenced by spatial, temporal, and climatic variability. Traditional monitoring and management methods often rely on manual observations or local measurements, which are time-consuming, costly, and limited in scale. In contrast, remote sensing technologies—through satellite, airborne, or unmanned aerial vehicle (UAV) platforms—offer the capability to collect high-resolution data across large areas and multiple timeframes (Souissi et al., 2022). These data streams provide crucial insights into soil moisture dynamics, vegetation growth, and land-use changes, forming the foundation for intelligent modeling and decision support.

Despite the growing body of research, several challenges persist. Data heterogeneity, model interpretability, and the scarcity of ground-truth datasets limit the robustness and transferability of AI–RS models across regions and crop systems. Therefore, this review aims to (i) summarize the current state of AI and remote sensing applications in environmental and agricultural engineering, (ii) identify key challenges and research gaps, and (iii) propose future directions for developing sustainable and scalable solutions.

2. Artificial Intelligence in Environmental and Agricultural Engineering

In recent years, Artificial Intelligence (AI) has emerged as a powerful tool in environmental and agricultural engineering, driving innovation and improving decision-making processes. AI techniques, such as machine learning, deep learning, and neural networks, are increasingly applied to monitor and analyze complex natural systems, including soil moisture, crop growth, and land-use changes. When combined with remote sensing (RS) technologies, AI enables precision agriculture practices, such as optimized irrigation, targeted

fertilization, and accurate crop yield prediction under variable climatic conditions. Additionally, AI-based models are being used in environmental monitoring to predict soil erosion, assess flood risks, and evaluate water quality variations, supporting sustainable resource management and climate resilience. These advancements highlight the potential of AI to transform traditional agricultural and environmental practices, contributing to food security, ecosystem conservation, and climate adaptation.

3. Remote Sensing Technologies and Data Sources

Remote sensing (RS) is the process of acquiring information about a specific object or area without direct physical contact, typically through the detection of electromagnetic radiation reflected or emitted by the target. This technology generates data in image form, enabling detailed monitoring and physical analysis of natural and agricultural systems. RS has become an essential tool for observing the Earth and other planetary bodies from distant locations, such as space, using satellites, as well as from unmanned aerial vehicles (UAVs) and ground-based sensors. Modern RS systems, including multispectral, hyperspectral, and radar sensors, provide high-resolution information on soil moisture, vegetation health, land use, and crop conditions. When combined with geographic information systems (GIS) and advanced analytics, these data allow for precise mapping, trend analysis, and predictive modeling. Consequently, RS supports a wide range of applications in agriculture, environmental monitoring, disaster management, and climate adaptation, facilitating informed decision-making and sustainable resource manageme

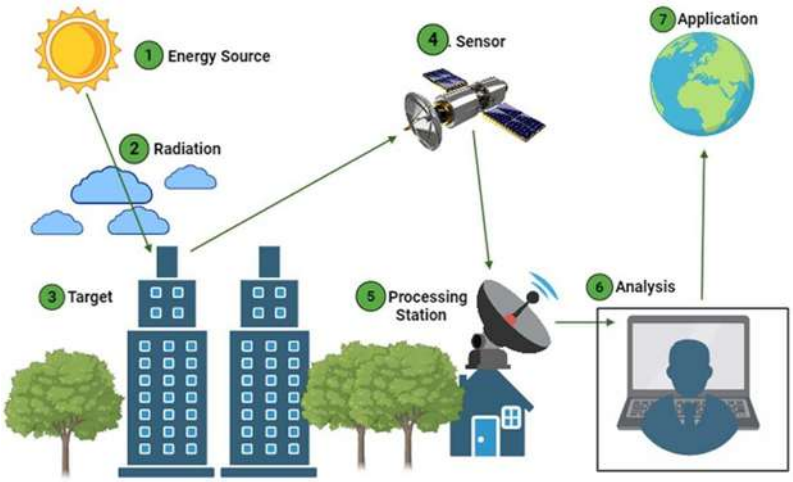

Figure 1. Principles of Remote Sensing with sequential steps (Sarker et al., 2025)

4. Integrated AI–RS Applications in Agriculture and Environment

The integration of Artificial Intelligence (AI) with Remote Sensing (RS) technologies has significantly advanced agriculture and environmental management. By combining the spatial and temporal coverage provided by RS with the predictive capabilities of AI, it is possible to monitor and model complex natural systems with high accuracy. In agriculture, AI–RS integration enables crop type classification, biomass estimation, disease and pest detection, and yield prediction, facilitating precision farming practices and resource optimization (Katkani et al., 2022; Espinel et al., 2024). Similarly, in environmental applications, these technologies support the assessment of soil health, water quality, land-use change, and ecosystem dynamics, while also aiding in the prediction of natural hazards such as floods and droughts (Boukita et al., 2025). The synergy of AI and RS improves the

efficiency and timeliness of data-driven decisions, contributing to sustainable resource management, climate adaptation strategies, and food security.

5. Crop Monitoring and Yield Prediction

Crop monitoring and yield prediction are among the most prominent applications of integrating Remote Sensing (RS) and Artificial Intelligence (AI) in modern agriculture. High-resolution satellite and UAV imagery allow continuous observation of vegetation dynamics, canopy structure, and photosynthetic performance, while machine learning and deep learning models enable the extraction of meaningful patterns for crop growth assessment. These techniques facilitate early detection of stress factors such as drought, nutrient deficiency, and disease, thereby improving decision-making for irrigation, fertilization, and pest control(Elwahab et al., 2023). Recent advancements demonstrate the effectiveness of combining multispectral and radar data with AI algorithms to estimate biomass and predict yields with high accuracy across diverse agricultural landscapes (Chen et al., 2023). Similarly, machine learning models trained on time-series satellite data have been shown to enhance yield forecasting at regional and national scales (Kerner et al., 2022). UAV-based hyperspectral imaging coupled with convolutional neural networks (CNNs) has further improved the capacity to detect stress responses and estimate crop productivity in real time (Ohyama et al., 2023). Together, these AI–RS approaches contribute to precision agriculture strategies aimed at increasing productivity, resource efficiency, and climate resilience. Remote sensing imagery such as RGB (Red–Green–Blue) and NDVI (Normalized Difference Vegetation Index) provides essential spatial information for monitoring crop development and predicting yield.For better clarity, several examples of NDVI and RGB images corresponding to the largest analysis window (40 m) are shown in Fig. 2, along with their associated yield values, where the color bar indicates the yield range. Images sharing the same identifier originate from the same field location. In this setup, the network's prediction target is defined as the mean yield within the analysis window corresponding to each input image. It is also worth noting that the RGB and NDVI models were trained independently to avoid errors caused by potential spatial misalignment between the two imagery datasets. This separate training strategy allows for a direct comparison of model performance and supports evaluating which data source, RGB or NDVI, offers more accurate yield predictions.

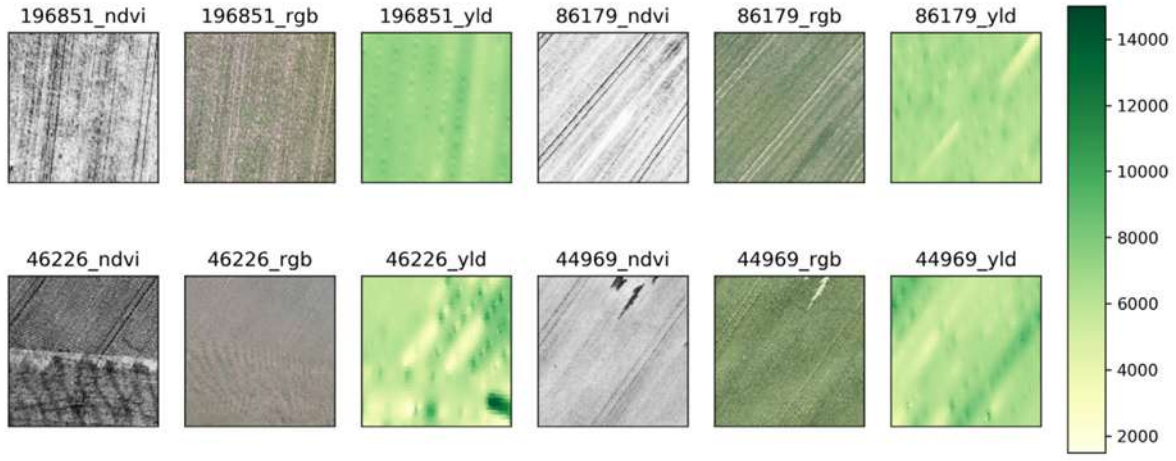

Figure 2. Visualizations of NDVI and RGB input images and yield targets. The identification numbers above the images denote the distinct area from which the images were extracted (Nevavuori et al., 2019)

6. Soil Salinity and Water Quality Assessment

Salinity represents one of the most critical constraints in agricultural production, particularly in arid and semi-arid regions where evapotranspiration rates are high and irrigation practices often lead to salt accumulation in soils. Recent advances in remote sensing have enabled the development of satellite-derived salinity indices, such as the Normalized Difference Salinity Index (NDSI), which provide large-scale and continuous monitoring of salinization dynamics (Elhag, 2019). The integration of these indices with machine learning models, including support vector machines and random forests, has significantly improved the accuracy of soil salinity assessment and spatial prediction (Mazarei et al., 2021). Additionally, artificial intelligence is increasingly utilized to evaluate water quality in reservoirs and irrigation systems. Remote sensing reflectance data combined with regression or neural network models allow the estimation of key water quality parameters such as chlorophyll-a, turbidity, and dissolved organic matter, supporting sustainable water resource management (Gholizadeh et al., 2020). To summarize the key indicators and methods used for soil salinity and water quality assessment, Table 1 presents the main parameters, measurement methods, AI/RS tools, and relevant references.

Table 1. Key indicators for soil salinity and water quality assessment using AI and remote sensing.

Parameter / Indicator	Measurement Method	Remote Sensing / AI Tool	Reference	Observations / Notes
Soil Salinity (EC, dS/m)	Soil sampling & laboratory analysis	NDSI (Normalized Difference Salinity Index), Machine Learning regression	Hermosilla et al., 2019; Sothe et al., 2021	High salinity detected in arid areas; correlated with poor crop growth
Soil Moisture (%)	Time-domain reflectometry, gravimetric method	Satellite-based soil moisture indices, Neural Networks	Merchant et al., 2022	Spatial variability captured with RS data
Water Quality (TDS, mg/L)	Laboratory chemical analysis	Regression models using satellite reflectance	Mazarei et al., 2021	AI predicts seasonal variations in reservoir water quality
Soil pH	Laboratory analysis	Spectral RS data + ML	Ismaili et al., 2023	Important for assessing soil suitability for crops
Sodium Adsorption Ratio (SAR)	Laboratory calculation	AI prediction models using NDSI & field data	Elhag et al., 2017	Indicates potential sodicity issues in irrigation water

7. Climate Change and Resource Management

Climate change poses significant challenges to global agriculture, water resources, and ecosystem management. Rising temperatures, altered precipitation patterns, and increased frequency of extreme events such as droughts and floods threaten crop productivity, soil health, and water availability. Effective resource management strategies are essential to mitigate these impacts and ensure sustainable food and water security (Elwahab et al., 2025). Recent advances in remote sensing and artificial intelligence (AI) have enabled the monitoring of climate-related changes in real time, allowing for better prediction of crop yields, water stress, and soil degradation. Integrating AI-driven models with historical climate and environmental data facilitates adaptive management practices, such as optimized irrigation scheduling, selection of climate-resilient crop varieties, and targeted soil conservation measure. Moreover, such approaches support policymakers and farmers in making informed decisions to enhance resilience to climate variability and sustain natural resource use over the long term (Mazarei et al., 2021; FAO, 2022).

8. Challenges and Limitations

Despite their significant potential, integrated AI–RS systems face several challenges and limitations. One major issue is data heterogeneity, as information collected from different sensors, regions, or crop types can vary in resolution, format, and quality, complicating model training and analysis. Limited availability of ground-truth data further constrains the accuracy and validation of predictions. High computational costs and the need for specialized hardware can impede large-scale implementation, especially in resource-limited contexts. Moreover, model transferability across different geographic regions and crop varieties remains a challenge, limiting the generalization of results. Ethical considerations, such as data privacy and the environmental impact of energy-intensive computations, must also be addressed to ensure sustainable and responsible deployment of AI in agricultural and environmental applications. Addressing these challenges is critical to unlocking the full potential of AI–RS systems for precision agriculture and environmental monitoring. Future research in environmental and agricultural monitoring should prioritize the integration of emerging technologies such as Internet of Things (IoT) sensors, edge computing, and digital twin frameworks to enable more accurate and real-time data acquisition and decision-making. The adoption of explainable artificial intelligence (XAI) methods can improve model interpretability, allowing experts to better understand and trust the predictions generated by AI systems. Additionally, the development and dissemination of open-access datasets, as well as collaborative platforms, will be crucial for democratizing AI tools and fostering innovation in sustainable agriculture and environmental management. Combining these approaches has the potential to enhance resilience to climate variability, optimize resource use, and support informed policy and management strategies for the future.

9. Conclusion

Artificial intelligence (AI) and remote sensing (RS) technologies have demonstrated remarkable potential in transforming environmental and agricultural engineering practices. Their integration allows for high-precision monitoring of crops, early detection of stress factors, optimized irrigation and fertilization, and improved prediction of yields under variable climatic conditions. Beyond agriculture, AI–RS systems support environmental management by assessing soil health, water quality, land-use changes, and ecosystem dynamics, thereby contributing to climate adaptation and natural resource sustainability. The continued evolution of data acquisition technologies, including high-resolution satellites, IoT sensors, and UAVs, coupled with advances in machine learning and explainable AI, is expected to enhance the accuracy, interpretability, and real-time applicability of these systems. Collaborative platforms and open-access datasets will further democratize access to AI tools, enabling researchers, policymakers, and farmers to make informed decisions and implement sustainable practices at regional and global scales. Overall, the synergistic use of AI and RS provides a promising pathway to address pressing global challenges such as food security, water scarcity, and climate change mitigation. By fostering interdisciplinary research and leveraging cutting-edge technologies, these approaches are poised to play a central role in building resilient and sustainable agricultural and environmental systems for the future.

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Thermal Instability of A Polymer Panel Reinforced with Glass Particulates

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Abstract
Water and oil reservoirs are commonly made from polymers. To enhance their mechanical strength, the technique of incorporating short glass particulates into the polymers is employed. This method improves the overall reliability of the reservoirs. The objective of this study is to analyze the thermal instability that occurs during the buckling of panels in these reservoirs. Previous research has shown that the addition of short glass particulates can negatively impact thermal buckling. In the first stage of this study, polymers will be mixed with 10% and 20% short glass particulates, and a calculation script will be developed to determine the thermal buckling behavior.

Research Article

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Polymers Reservoirs, Glass Particulates, Thermal Buckling, Mechanical Strength

1.Introduction

Polymer reservoirs are commonly used for the storage of water, oils, and petroleum products such as gasoline and diesel. These reservoirs can have cylindrical, ellipsoidal, square, or rectangular shapes. Like all structures, polymer reservoirs are subjected to mechanical and thermal loads. This study specifically focuses on the thermal loads applied to square or rectangular walls to assess the variation in the critical buckling temperature. Youssef Hilali et al. (2025) studied the thermal buckling and post-buckling behavior of functionally graded material (FGM) plates using a higher-order theory, demonstrating accurate predictions of structural responses (Hilali et al., 2025). Guangjie Han et al. (2025) investigated the buckling and post-buckling behavior of FGM plates reinforced with graphene nanoplatelets, showing that graphene significantly enhances the stiffness of the plates (Han et al., 2025). Han Zhang et al. (2019) conducted a comprehensive study on the buckling behavior of marine pipes, providing an overview of stability, buckling, and free vibration analysis of FGM structures (Zhang et al., 2019). Irina Vikhareva et al. (2021) examined biodegradable polymer materials modified with microstructured titanium phosphate under thermal loading and concluded that the modified polymers outperform conventional polymers (Vikhareva et al., 2021). Joris Doumouro et al. (2021) quantitatively analyzed heat transfer between particulates at the micrometer scale, offering precise measurements of thermal contact resistance (Doumouro et al., 2021). Ike (2025) conducted a study on plate buckling using the Galerkin method (Ike, 2025), and also investigated the buckling of Euler-Bernoulli beams resting on elastic foundations (Ike, 2024a). Further, Ike (2024b) analyzed beam buckling using the Ritz variational method with two foundation parameters (Ike, 2024b). Turan et al. (2024) studied the buckling of orthotropic FGM plates considering shear deformation effects (Turan, 2024). Finally, Turan et al. (2025) analyzed the lateral-torsional stability and various buckling behaviors of structural elements under uniform mechanical or thermal loading, taking shear deformation into account (Turan et al., 2025). Numerous studies have focused on improving concrete properties. Harrat et al. (2021) examined the agglomeration of nanosilica in concrete applied to beams, highlighting its influence on structural performance (Harrat et al., 2021). Chatbi et al. (2022) evaluated the effect of nanosilica in slabs resting on elastic foundations, demonstrating enhanced bending behavior (Chatbi et al., 2022). Benfrid et al. (2023) investigated the thermomechanical performance of panels incorporating glass powder, providing a detailed evaluation of limitations and performance (Benfrid et al., 2023). Elhennani et al. (2023) analyzed beams reinforced with three types of nanoparticles, considering buckling and free vibration on multi-parameter elastic foundations (Elhennani et al., 2023). Kechir et al. (2024) conducted a study on beams with nano-sized iron oxide particles, showing improved mechanical performance and bending behavior (Kechir et al., 2024). Several researchers have studied metal-based fibers. Błaszczyński and Przybylska-Fałek (2015) demonstrated that the addition of steel fibers increases the critical compression load (Błaszczyński and Przybylska-Fałek, 2015). Khaloo and Afshari (2005) affirmed that fiber-reinforced slabs exhibit improved deflection resistance (Khaloo and Afshari, 2005). Mohod (2012) noted a slight reduction in workability but a significant increase in mechanical strengths (Mohod, 2012). Other studies, such as those by Mujalli et al. (2022), indicated approximately a 2% improvement in the performance of steel fiber-reinforced concrete compared to conventional concrete (Mujalli et al., 2022).

This study aims to address two key issues. The first is the homogenization of polymers with glass particulates at 10% and 20%. The second is a thermal buckling case study using the First-Order Shear Deformation Theory (FSDT) for plates.

2. Material and Method

2.1. Homogenization

For the homogenization process, the mixing method was examined to determine the thermo-mechanical properties of polymers mixed with glass particulates. For the polymers, the elastic modulus is 2 GPa, the Poisson's ratio is 0.2, and the thermal expansion coefficient is 80 × 10^{-6} /°C. For glass particulates, the elastic modulus is 70 GPa, the Poisson's ratio is 0.16, and the thermal expansion coefficient is 7 × 10^{-6} /°C (Chawla, 2000; Mallick, 2000). A decrease in both mechanical and thermal properties is observed with the incorporation of glass particulates.

$$X_f = X_c * V_c + X_s * V_s$$

Table 1. The thermomechanical properties.

Vf (%)	The elastic modulus (GPa)	The thermal expansion coefficient (10^{-6} /°C)	The Poisson's ratio
0	2	80.1	0.22
10	8.9	72.9	0.2
20	15.7	65.6	0.19

2.2. Study of thermal buckling

En utilisant la référence (Sayyad and Ghugal, 2014), créez un script de calcul capable de calculer le flambage thermique.

$$NO := \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{\alpha hom \cdot Ehom \cdot \Delta T \cdot \alpha hom}{(1 - \nu hom)} \, dz$$

2.3. Validation

To validate the FSDT program, it must be compared with a small deflection program (Cheng, 2018). Below is Table 2.

Table 2. The validation of the results through comparison between X chang (Cheng, 2018) and the currently available program script (FSDT).

References	X. Cheng (SD)[16]	Present FSDT
b=a; a=30h	146.6	160.7
b=3a;a=30h	87.1	89.2
b=a;a=40h	88.1	90.4
b=3a;a=30h	48.9	50.2

3. Results and Discussion

The critical buckling temperature of polymer panels reinforced with glass particulates is shown for both square panels (Table 3) and rectangular panels with a length/width ratio of 2 (Table 4).

Table 3. The variation of the critical temperature for the square plate.

a/h; a=b	0%G-F	10%G-F	20%G-F
5	49.7	60.4	75.0
10	14.2	17.2	21.4
15	6.5	7.9	9.7
20	3.7	4.5	5.5
25	2.4	2.9	3.6
30	1.6	2.0	2.5
35	1.2	1.5	1.8
40	0.9	1.1	1.4
45	0.7	0.9	1.1
50	0.6	0.7	0.9

Table 4. The variation of the critical temperature for the rectangular plate.

a/h; a=b	0% G-F	10%G-F	20%G-F
5	29.8	36.2	44.9
10	8.0	9.8	12.1
15	3.6	4.4	5.5
20	2.1	2.5	3.1
25	1.3	1.6	2.0
30	0.9	1.1	1.4
35	0.7	0.8	1.0
40	0.5	0.6	0.8
45	0.4	0.5	0.6
50	0.3	0.4	0.5

The variation in critical buckling temperature for both square and rectangular plates follows similar trends. For square plates, the critical temperature decreases as the a/h ratio increases, indicating that thicker panels are more resistant to thermal buckling. The addition of glass particulates significantly improves the critical temperature, with the highest improvement observed at a 20% glass particulates content. For example, at a/h = 5, the critical temperature increases from 49.69°C for pure polymers to 74.97°C for 20% glass particulates reinforced polymers. However, the rate of improvement diminishes as the a/h ratio increases. For higher a/h values (e.g., 50), the increase in critical temperature is smaller, ranging from 0.59°C for pure polymers to 0.89°C for 20% glass particulates reinforced polymers. For rectangular plates, similar trends are observed, with the critical temperature decreasing as the a/h ratio increases. The overall effect of glass particulates reinforcement is also significant, especially at 10% and 20% particulates content. At a/h = 5, the critical temperature for pure polymers (0% s-f) is 29.79°C, while for 20% glass particulates, it increases to 44.91°C, indicating the positive influence of glass particulates on thermal stability. Again, as the a/h ratio increases, the improvement in critical temperature with the addition of glass particulates becomes less

pronounced. At a/h = 50, the critical temperature rises from 0.33°C for pure polymers to 0.50°C for 20% glass particulates reinforced polymers.

4. Conclusion

The addition of glass particulates to polymers significantly enhances their thermal buckling resistance, particularly for thinner panels. This improvement is most noticeable at lower a/h ratios and diminishes as the panels become thicker. Glass particulates-reinforced polymers are thus especially suitable for applications where improved thermal stability is essential.

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