TÜRKİYE VE DÜNYADA TOPRAK BİLİMİ VE BİTKİ BESLEME

Editör: Prof.Dr. Sevinç YEŞİLYURT

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İÇİNDEKİLER

KIRMIZI ALG VE ÇEVRE: DOĞAL DENGENİN SESSİZ KAHRAMANLARI

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1. GİRİŞ

Algler fotosentetik yetenekleri sayesinde ekosistemlerin birincil üreticileri olarak doğal döngülerin sürdürülebilirliğinde önemli bir rol oynamaktadır. Genel olarak mikroalgler ve makroalgler olarak büyüklük esasına göre sınıflandırılan algler, fotosentez için gerekli klorofil ve diğer pigmentlere sahip olup tatlı ve tuzlu sularda, nemli topraklarda, kaya ve ağaçlar üzerinde bulunabilirler (Shalaby, 2011). Toprak algleri, sucul ekosistemlerde yaşayan alglere kıyasla daha küçük boyutlu ve yapısal olarak daha basittir. Çoğunluğu klorofil içeren fotosentetik organizmalar olan algler, enerji gereksinimlerini güneş ışığından, karbon ihtiyaçlarını ise atmosferdeki karbondioksitten karşılarlar ve bulundukları ortama oksijen sağlamaktadır. Atmosferdeki oksijenin büyük kısmı karasal ormanlar yerine okyanuslar ve tatlı sularda yaşayan mikroskobik fotosentetik canlılar olan Fitoplanktonlar ve Algler tarafından sağlanmaktadır (Chapman, 2013; Kolcu & Yeşilyurt, 2025). Dünya üzerindeki tarihi 3,5 milyar yıl öncesine kadar dayanan fotosentez yeteneğine sahip bu canlı türü klorofil içeren yüksek protistalardır ve protein ile A, C, D ve E vitaminleri açısından

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zengin bir besin kaynağı olup nem, besin ortamı ve güneş ışığı bulunan ortamlarda gelişmektedirler (Spínola et al., 2024). Algler gıda ve besin takviyelerinden ilaç ve kozmetik endüstrisine, enerji üretiminden çevre bilimi alanında atık su arıtımına, tarımda ise Biyo-gübre ve toprak düzenleyici olarak birçok farklı kullanım alanında bizim fark etmediğimiz pek çok doğal süreci yöneten ve içinde yer alarak önemli katkılar sunmaktadır (Ak, 2015; Şirinyıldız & Yorulmaz, 2022; Kolcu & Yeşilyurt, 2025). Toprak bilimi açısından değerlendirildiğinde Algler; organik madde birikimi, toprak yapısının iyileştirilmesi, nem tutma kapasitesinin artırılması ve mikrobiyal çeşitliliğin desteklenmesinde fayda sağlamaktadır. Ayrıca algler, erozyonun azaltılmasında, azot ve fosfor döngüsünün düzenlenmesinde ve kirleticilerin biyolojik arıtımında etkili doğal ajanlar olarak öne çıkmaktadır. Tek hücreli organizmalardan devasa çok hücreli formlara kadar geniş bir morfolojik çeşitlilik gösteren ve hemen her ekosistemde bulunan bu canlı grubu klorofil içerikleri sayesinde ototrof beslenirler ve basit bir talus yapısına sahip olmalarına rağmen ekosistemler üzerinde önemli etkiler yaratırlar (Zhang & Hu, 2011). Tatlı su ve deniz ekosistemlerinin yanı sıra ekstrem çevre koşullarında da yaşamlarını sürdürebilen algler, toprak ekosistemlerinde organik madde birikimi, mikrobiyal çeşitliliğin desteklenmesi ve toprak yapısının iyileştirilmesi gibi süreçlerde kritik roller üstlenir. Üreme stratejilerindeki çeşitlilik ve çevresel değişimlere yüksek adaptasyon yetenekleri, alglerin sürdürülebilir tarımsal üretim ve ekolojik denge açısından değerini artırmaktadır. Bu özellikleri sayesinde algler, tarımsal alanlarda Biyo-gübre ve toprak düzenleyici olarak kullanılabilmekte, toprak verimliliğini ve çevresel sürdürülebilirliği desteklemektedir (Sahoo & Baweja, 2015;Kolcu & Yeşilyurt, 2025). Deniz yosunu olarak da adlandırılan makroalgler çıplak göz ile görülebilen çok hücreli organizmalar olup içerdikleri renk pigmentlerine göre üç taksonomik gruba ayrılır: Kırmızı algler (*Rhodophyta*), Yeşil algler (*Chlorophyta*) ve Kahverengi algler (*Heterokontophyta*) (Park et al., 2024). Kırmızı algler bitki aleminin en kadim ökaryotik soylarından birini temsil ederken fosil kayıtları uzak geçmişe kadar uzanmaktadır. Bu grup, özgün pigmentleri olan fikobilinler sayesinde belirginleşir ve diğer alglerden farklı olarak hareket organeli olan kamçıları ve hücre bölünmesiyle ilişkili sentriollere sahip değildir. Ayrıca yaşam döngüleri karmaşık ve aşamalı bir yapıda ilerlerken hücre duvarlarında biriktirdikleri agar ve karragenan gibi değerli hidrokolloitler onlara ticari bir önem kazandırmaktadır (Zheng & Zhuang, 2025). Bu derleme makalede doğal dengenin korunmasında işlevli kırmızı algleri tanıyarak sürdürülebilir bir çevre için kullanım alanlarına değinmek ve gelecek için alglerin sağladığı faydalar hakkında daha kapsamlı çalışmalar yapılmasına öncülük etmek amaçlanmıştır.

2. KIRMIZI ALGLER

Kırmızı algler ya da *Rhodophyta,* filogenetik olarak en eski alt bitki gruplarından birini oluşturan ve yaklaşık 5.000 tür içeren geniş bir takson olarak kabul edilir (Usov, 2011). Bu kırmızı organizmalar basit bir anatomiyi ve çok çeşitli yaşam döngülerini koruyan, sucul, fotosentetik bir bitki grubudur. Morfolojik olarak tek hücreli veya çok hücreli yapılar sergileyebilirler. Bu grubun yaklaşık %98'i denizel habitatlarda baskındır, geri kalan yalnızca %2'lik kısmı tatlı sularda bulunur ve çok az sayıda tür karasal/subaerial yaşam biçimine sahiptir. Planktonik tek hücreli türler, düzenli olarak gerçekleşen ikili bölünmeye dayanan basit yaşam döngülerine sahiptir. Buna karşılık gelişmiş makroskobik türlerde trikogami, üç evreli ve haplo-diplobiontik bir yaşam döngüsü görülür; bu döngü, bir haploid (gametofitik) aşama ile iki diploid (karposporofitik ve tetrosporofitik) aşamadan oluşur. Yeşil algler ve yüksek bitkiler ile tek bir ortak atayı paylaştıkları için gerçek bitkiler arasında değerlendirilen kırmızı algleri diğer alg gruplarından ayıran belirgin özellikler vardır: kamçı ve sentriyollerin tamamen bulunmaması, kloroplastlarda fıkobilizomların ve üst üste dizilmemiş tilakoitlerin yer alması, parankima dokusunun gelişmemiş olması ve hücre bölünmesinin tam gerçekleşmemesi sonucunda oluşan çukur bağlantıların (pit-connection) varlığı bunların başlıcalarıdır. Kırmızı alglerde görülen tipik kırmızı ton ve bunun çeşitli değişimleri, klorofiller ve karotenoidler gibi fotosentetik pigmentlerin yanında ışık toplama görevi üstlenen fıkobilizomların katkısıyla ortaya çıkar. Bu yapılar, üç temel gruba ayrılan suda çözünebilen protein kökenli pigmentlerden (fikoeritrin, fikosiyanin ve alofikosiyanin) oluşur (Cotas et al., 2022; Shah, 2023). Kırmızı alglerin yağ asitleri, vitamin, protein, polisakkarit gibi çeşitli yapısal bileşikler açısından zengin bir kaynak oluşu sayesinde tarım, gıda, tıp ve birçok endüstriyel alanda önemini korumaktadır. Gıda endüstrisinde jelleşme ve kıvam artırıcı özellikleri nedeniyle katkı maddesi olarak kullanılırken tıpta antibakteriyel özellikleri ön plana çıkar ve tarımda ise gübreleme ve toprak düzenleyici olarak kullanımı sayesinde faydaları ve varlığı göz ardı edilemeyecek umut verici önemli bir türü oluşturur (Alves et al., 2019; Kolcu & Yeşilyurt, 2025).

2.1. Kırmızı Alg ve Deniz Ekosistemleri

Deniz ekosistemi okyanusları, denizleri, mercan resiflerini, gelgit bölgelerini ve haliçleri de kapsayan en büyük sucul ekosistemdir. Canlı ve cansız bileşenlerin etkileşimi ile oluşan deniz ekosistemi besin zincirinin temelini oluşturan mikroskobik fitoplanktonlar ve deniz yosunları aracılığı ile dünya oksijeninin büyük kısmını üretme yeteneğine sahiptir. Balıkçılık ve turizm gibi ekonomik faydalarının yanı sıra küresel düzeyde hava ve iklim dengesini koruyarak yaşam kaynağı oluşturur (Kayhan vd., 2015). Deniz ekosistemlerindeki fotosentetik organizmaların önemli bir kısmını oluşturan kırmızı algler, klorofil-a ve özellikle fikoeritrin pigmentleri sayesinde fotosentez yapmaktadır. Fikoeritrin, mavi ve yeşil ışığı absorbe etme özelliği sayesinde kırmızı alglerin diğer alg türlerine göre daha derin sularda yaşamasını ve fotosentez yapmasını kolaylaştırır ve deniz canlılarının solunumu için gerekli oksijeni üretirler (Ilter et al., 2017). Küçük deniz salyangozları, deniz kestaneleri ve bazı balık türleri gibi birincil tüketicilere doğrudan besin kaynağı sağlayan alglerin ürettiği organik bileşikler ve ölen alglerin besin ağındaki mikroorganizmalar için beslenme girdisi oluşturması ekosistemdeki dengeyi sağlamaya yardımcı olur. Su kalitesinin düzenlenmesinde özellikle *Gracilaria* gibi bazı kırmızı alg türleri sudaki aşırı azot ve fosfat bileşiklerini bünyesine alarak doğal bir biyofiltre görevi üstlenir (Chopin et al., 2001). Kırmızı alglerin dallı, yapraksı ve jelatinimsi yapıları deniz ekosistemlerindeki canlılar için bir tür saklanma, beslenme ve üreme alanı oluşturur. Mercan resiflerinin çekirdeğini güçlendirici kalsiyum karbonat salgıları sayesinde dalga etkisini keserek resifler içindeki canlılar için korunaklı yaşam alanı sunar ve ayrıca ekosistemdeki doğal dengeyi sağlamada daha birçok görevi üstlenerek paha biçilemez değere sahip olduklarını kanıtlamışlardır (Silva, 2022).

2.2. Kırmızı Alg ve Agar/Agaroz

Kırmızı algler, diğer alg sınıflarına kıyasla birçok biyolojik olarak aktif metabolitin en önemli kaynağı olarak kabul edilmektedir. Deniz yosunlarının temel kullanımı insan gıdası kaynağı ve zamk (fikokolit) kaynağı olmasıdır. Agar, aljinik asit ve karragenan gibi fikokolloidler, esas olarak kahverengi ve kırmızı alg hücre duvarlarının bileşenleri olup endüstride yaygın olarak kullanılırlar (El Gamal, 2010). Agar, kırmızı alglerden elde edilen kuru ve şekilsiz bir karbonhidrattır. Isıtılınca eriyip sıvılaşan ve soğutulunca jel haline gelen termal geri dönüşümlü bir madde olup kırmızı alg türlerinden (özellikle *Gracilaria*, *Gelidium, Pterocladia, Acanthopeltis* ve *Ahnfeltia* cinslerinden) su ekstraksiyonu yoluyla elde edilen bir polisakkarit karışımıdır. Dünya genelindeki agar üretiminin büyük çoğunluğu bu alg türlerinden sağlanır. Agarın yapısı, jelleşme gücünün temel kaynağı olan agaroz (%70) ve daha düşük jelleşme özelliği gösteren agaropektin (%30) olmak üzere iki ana polisakkaritten meydana gelmektedir. Agaropektin, sülfatlı yapısıyla agarın genel bileşimine katkıda bulunurken sülfat, pürivat ve metoksi grupları da agarın kimyasal yapısının ayrılmaz parçalarıdır (Aktar & Cebe, 2010; Ilter et al., 2017). En belirgin özellikleri sulu ortamda eşsiz bir jel oluşturma gücüne sahip olması ve bu jelleri oluşturmak için potasyum, kalsiyum gibi reaktiflere veya yüksek şeker konsantrasyonu ya da asidik ortamlara ihtiyaç duymamasıdır. Geniş bir pH (5 ile 8 arasında) aralığında kullanılabilir. Agar, yüksek sıcaklıklara (100°C'nin üzeri) mükemmel ısı dayanımı göstererek etkili sterilizasyona olanak sağlamaktadır. Bu yönüyle %1,5'lik agar çözeltisi 32–43°C'de jel oluşturur ve 85°C'nin altında erimediği için diğer jelleştiricilerden ayrılmaktadır. Gıda uygulamaları için ideal olan agar aromasız ve şeffaf yapısıyla içerisine karıştırılan ürünlerin aromalarını özümseyip zenginleştirir ve koku sabitleyici görevi görmektedir. Son olarak Agar jeli orijinal özelliklerini kaybetmeden kolayca geri dönüştürülebilir, tekrar tekrar eritilip yeniden jelleştirilebilir (Armisen & Galatas, 1987).

2.3. Kırmızı Alglerin Karbon Tutma Kapasitesi

Atmosferdeki karbondioksit seviyelerinin artışıyla tetiklenen küresel ısınma tehlikesi, bilim insanlarını ve araştırmacıları karbonu verimli bir şekilde biyolojik olarak sabitleme yeteneğine sahip organizmalara odaklanmaya yöneltmiştir. Bu organizmaların karbon tutma mekanizmalarının anlaşılması ve optimize edilmesi, biyo-mühendislik çözümleri aracılığıyla karbon emisyonlarını azaltma ve hatta geri çevirme potansiyeli taşıdığı için büyük bir önem kazanmıştır. Fotoototrofik algler tarafından gerçekleştirilen karbon fiksasyonu, karbondioksitin atmosfere salınımını azaltma ve küresel ısınma eğilimini hafifletmeye yardımcı olma potansiyeline sahiptir. Özellikle kıyı ve deniz ekosistemlerinin birincil üreticileri olan fitoplankton, deniz yosunları ve deniz çayırları gibi canlılar bu karbon tutma görevini karasal bitkilere göre çok daha yüksek bir verimlilikle yerine getirirler. Bu denizel biyokütle, karbondioksiti hızla bünyesine bağlayarak onu uzun süreler boyunca okyanusun derinliklerinde veya tortularda depolayabilen üstün karbon tutucu ajanlar olarak kabul edilir (Kaladharan et al., 2009). Kabuklu mercanlar, kırmızı algler (*Rhodophyta*) grubunun Corallinaceae ailesine ait özel bir alt türüdür. Bu algler, fotosentez yoluyla organik karbon depolamanın yanı sıra kalsiyum karbonat biriktirerek inorganik karbonu da uzun süreli ve kararlı bir şekilde saklayabilirler. Böylece hem deniz ekosistemlerinde resif oluşumunu destekler hem de atmosferdeki karbonun önemli bir kısmının uzun vadeli tutulmasına katkı sağlayarak iklim değişikliğiyle mücadelede önemli bir rol oynarlar (Büdenbender et al., 2011; Kolcu & Yeşilyurt, 2025).

2.4. Kırmızı Alg ve Antibakteriyel

Kırmızı algler; yapılarında bulunan sülfatlanmış polisakkaritler, fenolik bileşikler ve diğer biyolojik olarak aktif metabolitler aracılığıyla çeşitli bakteri türlerinin gelişimini baskılayabilme yeteneğine sahiptir. Bu durum, kırmızı alglerin doğal antibakteriyel aktivite gösterdiğini ortaya koymaktadır. Söz konusu biyolojik özellikler, kırmızı algleri sentetik koruyucu ve antibiyotiklere alternatif olarak gıda muhafazası, doğal antimikrobiyal ajan geliştirilmesi ve farmasötik ürün tasarımı gibi alanlarda dikkate değer bir biyokaynak haline getirmektedir. Bu bağlamda, kırmızı alglerin antibakteriyel potansiyelinin değerlendirilmesi, sürdürülebilir ve çevre dostu biyoteknolojik uygulamalar açısından önemli bilimsel ve endüstriyel fırsatlar sunmaktadır (Bhagat & Bedi, 2023). Albayatı ve ark. (2019), *Jania rubens* türünün metanol ve kloroform ekstrelerinin, test edilen tüm mikroorganizmalara karşı yüksek antibakteriyel aktiviteye sahip olduğunu bildirmiştir. *Laurencia* cinsi tarafından üretilen halojenli bileşikler, patojenik bakterilere karşı yüksek düzeyde antibakteriyel aktivite göstererek alglerin kimyasal savunma mekanizması olarak işlev görmektedir. Bu doğal kimyasallar, güçlü aktiviteleri nedeniyle antibiyotik direncini yenmeye yönelik yeni ilaçların geliştirilmesi için önemli bir öncü bileşik kaynağı potansiyeli taşımaktadır (Vairappan, 2003). Omar et al. (2012) tarafından yapılan çalışmada Cidde şehrinden toplanan *Chlorophyta, Phaeophyta* ve *Rhodophyta* familyalarına ait deniz yosunlarının antibakteriyel aktivitesi araştırılmıştır. Tüm deniz yosunu özütleri test edilen bakterilere karşı geniş spektrumlu antibakteriyel aktivite göstermiştir. Fatima et al. (2020) yaptığı çalışmada kırmızı alg P. hornemannii'nin sulu ham maddesi kullanılarak ilk kez Gümüş Nanopartiküllerin (Ag NP'ler) biyolojik olarak üretilebileceğini ve üretilen Ag NP'ler özellikle su ürünleri patojenleri olan *Vibrio parahaemolyticus*, *Vibrio vulnificus*, *Vibrio harveyii* ve *Vibrio anguillarum*'a karşı önemli antimikrobiyal aktivite sergilediğini bildirmiştir.

2.5 Kırmızı Algler ve Biyoremediasyon

Biyoremediasyon, doğal ekosistemlerde zaten var olan biyolojik süreçlerden yararlanarak çevresel kirliliğin kontrol altına alınmasını amaçlayan, çevreyle uyumlu, sürdürülebilir ve çoğu zaman ekonomik açıdan avantajlı bir iyileştirme yaklaşımıdır. Bu yöntemde, başta bakteriler, mantarlar ve algler olmak üzere çeşitli mikroorganizmaların, bazı durumlarda ise bitkilerin sahip olduğu metabolik ve fizyolojik kapasiteler kullanılarak kirletici maddelerin ortamdan uzaklaştırılması sağlanmaktadır. (Gürgan et al., 2022; Mukherjee et al., 2023). Alglerin biyoremediasyondaki en dikkat çekici uygulaması, atık sulardan ve deniz ortamlarından ağır metal iyonlarının giderilmesidir. Bu süreç, biyosorpsiyon olarak bilinir ve biyosorpsiyon yönteminde biyokütle olarak; bakteri, alg, mantar, maya gibi pek çok farklı mikroorganizma türü kullanılabilir (Aslan et al., 2007). Algler temel biyolojik ihtiyaçları olan proteinleri, nükleik asitleri ve hücre zarlarını üretmek amacıyla sudaki aşırı azot ve fosfor bileşiklerini aktif taşıma mekanizmalarıyla metabolik olarak hücrelerinin içine almaktadır. Bu besinlerin alg biyokütlesi içinde hapsedilerek sudan uzaklaştırılması sürecine biyofiltrasyon denir ve ötrofikasyon riskini azaltmada kritik rol oynamaktadır (Arumugam et al., 2018). Deniz yosunlarından elde edilen ekstreler, biyoremediasyon ve tarım teknolojilerinde giderek artan bir öneme sahiptir. Bu ekstreler, bitki gelişimini doğrudan teşvik eden ve aynı zamanda toprağın doğal mikrobiyal biyokütlesini ve aktivitesini uyararak besin döngüsü verimliliğini artıran ve kirleticilerin parçalanmasını hızlandırarak dolaylı yoldan toprak sağlığını ve biyoremediasyon potansiyelini önemli ölçüde iyileştiren zengin biyoaktif bileşikler içerir (Khan et al., 2009; Gürgan Adiloğlu, 2020). Tüm bu özellikleri göz önüne alındığında alglerin çevresel kirlilikle baş etme potansiyelinin biyoremediasyon uygulamalarında sürdürülebilir bir yaklaşımla ilerleyebileceğini ve biyoremediasyon uygulamalarına daha fazla önem verilerek alglere olan ilginin artması gerektiği inkâr edilemez gerçektir.

2.6. Kırmızı Algler ve Fitoremediasyon

Fitoremediasyon, çevresel ortamlarda bulunan kirleticilerin ortamdan uzaklaştırılması ya da toksisitelerinin azaltılması amacıyla bitkiler ve alglerin biyolojik kapasitelerinden yararlanan, ekonomik ve çevre dostu bir yaklaşımıdır. Bu yöntemde kullanılacak bitki türlerinin yüksek düzeyde metal alım ve biriktirme yeteneğine sahip olması, aynı zamanda ekosistemin dekontaminasyon sürecini hızlandırabilecek fizyolojik ve adaptif özellikler göstermesi beklenmektedir. Bitkilerin çok sayıda ağır metali bünyelerinde biriktirebildiği çeşitli çalışmalarla ortaya konmuştur (Yeşilyurt, 2023; Yeşilyurt & Gürgan, 2023). Bitkilerde ağır metal toleransı; metal iyonlarının hücre duvarı bileşenlerine bağlanarak hareketsizleştirilmesi, sitoplazmadan uzaklaştırılarak vakuollerde bölmelere ayrılması veya detoksifikasyon mekanizmaları yoluyla daha az zararlı formlara dönüştürülmesi gibi süreçlerle sağlanabilmektedir. Bu özellikler, fitoremediasyonu kirlenmiş alanların iyileştirilmesinde etkili ve sürdürülebilir bir teknoloji haline getirmektedir. Bazı algler, tolerans mekanizmalarının bir sonucu olarak yüksek ağır metal birikim kapasitesi gösterir ve birçok alg, ağır metallerle kompleks oluşturabilen ve onları vakuollere aktarabilen fitokelatinler ve metallotiyoneinler sentezler. Alglerin Fitoremediasyonda kullanılmasının bir diğer avantajı, bu türlerin yüksek biyokütle üretimi olması olup bu da yüksek ağır metal absorpsiyonuna ve birikimine yol açmasıdır (Chekroun & Baghour, 2013). Ağır metal iyonları içeren suların arıtılmasında bitkilerin ve özellikle alglerin kullanımı oldukça etkilidir. Fitoremediasyon, ucuz ve çok yüksek arıtma verimliliğine sahip olması nedeniyle giderek daha fazla kullanılan bir yöntemdir (Adiloğlu, 2018; Diaconu et al., 2023). Ağır metallerin geleneksel yöntemlerle giderilmesi metal konsantrasyonu çok yüksek olmadığında maliyetli ve verimsizdir. Alglerin metal biriktirme kapasitelerinin yüksek olması, farklı test materyallerine duyarlı olmaları, besin gereksinimlerinin bilinmesi, birkaç gün içinde yoğunluğu ve toksik maddenin neden olduğu etkiyi belirlemeyi sağlayan yüksek büyüme hızına sahip olmaları ve laboratuvarda kullanımlarının nispeten basit olması nedeniyle besin maddelerinin giderilmesinde kullanım için büyük bir potansiyele sahip olduğu düşünülmektedir (Adiloğlu & Gürgan, 2020; Yeşilyurt & Gürgan, 2023; Herrera-Cabrera et al., 2024).

3. SONUÇ

Kırmızı algler, geleneksel endüstrilerde önemli bir hammadde olan agarın elde edilmesinde temel bir kaynak olmanın ötesinde, çevresel kirliliğin azaltılması ve karbon döngüsünün yönetimine yönelik yenilikçi ve sürdürülebilir yaklaşımlar sunmaktadır. Çok yönlü kullanım potansiyeline sahip bu organizmalar; biyoremediasyon, karbon tutumu ve ekosistem iyileştirme süreçlerindeki rolleri sayesinde çevresel açıdan stratejik bir biyolojik kaynak olarak öne çıkmaktadır.

Bununla birlikte, kırmızı alglerin sahip olduğu zengin biyoaktif bileşik içerikleri; antioksidan, antimikrobiyal ve farmakolojik özellikleri nedeniyle sağlık ve ilaç endüstrileri açısından da yüksek bir katma değer sağlamaktadır. Bu bağlamda, gelecekte gerçekleştirilecek bilimsel çalışmaların kırmızı alglerin çevresel sürdürülebilirliğe katkıları ve biyoteknolojik potansiyelleri üzerine daha yoğunlaşması, söz konusu organizmaların ekolojik ve ekonomik değerinin daha kapsamlı biçimde ortaya konulması açısından büyük önem taşımaktadır.

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THE RELATIONSHIP BETWEEN PERIODICITY AND PLANT NUTRITION IN FRUIT TREES

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1. INTRODUCTION

Agriculture is one of the oldest production activities in human history, and the earliest comprehensive policies in the world were shaped in this field. Agriculture has maintained its strategic importance in every period because it constitutes the fundamental source of food. For this reason, throughout history, countries have aimed to develop their production capacity, reduce external dependency, and ensure self-sufficiency in food production. Fruit growing also has a very significant role within agricultural production; the fruit industry constitutes one of the most important components of the agricultural sector, encompassing the production, processing, and distribution of a wide variety of fruits consumed worldwide. Fruit production, which forms the most crucial part of this sector, is an important chain of agricultural activities with multidimensional effects on nutrition. Fruit cultivation is steadily increasing worldwide. As of 2023, the total area allocated to fruit production in the world has exceeded 68 million hectares, and the amount of fruit produced from this area has reached 870 million tons (Farmonaut, 2024). In Türkiye, it has been reported that approximately 3,700 hectares

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of land yielded 27.4 million tons of fruit production in 2023 (TÜİK, 2023).

The fruit-growing sector, which consists of activities such as the production, processing, storage, and distribution of fruits, not only makes a significant contribution to the global economy but also plays a critical role in food security and nutrition. The fruits produced attract great interest from consumers not only because of their taste but also due to their areas of use and their benefits to human health, and they influence the dietary habits of consumers across different continents. Meeting consumers' demands for high-quality, reliable, and affordable products for healthy nutrition positively affects the level of social welfare. This welfare results not only from consumer satisfaction but also from producer satisfaction. The economic profit obtained by producers from the fruits they cultivate is among the primary factors affecting their stability in production. Thanks to the profit generated from production, production areas can be expanded, modern agricultural methods can be employed, and more knowledgeable and professional cultivation practices can be carried out (Şener et al., 2020).

Producers often do not possess the effective knowledge and methods necessary to ensure and maintain stable year-to-year production in many fruits under traditional agricultural practices. One of the most important factors affecting stability and sustainability in production is the phenomenon of periodicity, which causes fruit trees to bear fruit one year and produce very little or no fruit in the following year. Periodicity refers to the significant decrease in yield obtained in a given year compared to the previous year, particularly in fruit trees.

In this section, information is provided on periodicity and its relationship with plant nutrition.

2. WHAT IS PERIODICITY?

Periodicity refers to the phenomenon in fruit trees in which fruit species and cultivars bear fruit one year and produce little or no fruit in the following year. Therefore, the annual fruit yield fluctuates between high and low crop loads, and this situation is also referred to as alternate bearing from year to year (Smith and Samach, 2013). Among producers, it is also described as “on-year–off-year,” and cases in which an off-year occurs after two or three consecutive on-years are also encountered. Periodicity is a phenomenon observed in many fruit species and cultivars. The degree of periodicity seen in fruit trees may vary depending on the species and even among cultivars within the same species. Periodicity is classified into two groups based on the crop load in the year when the yield is high: the phenomenon in which trees bear a heavy crop one year and no fruit the following year is called “absolute periodicity,” while the phenomenon in which trees bear a heavy crop one year and a reduced crop the next year is called “partial periodicity” (Serdar, 2025).

2.1. Which plants exhibit periodicity?

The occurrence of periodicity is observed most frequently in olive. In addition, it is commonly encountered in major fruit species such as apple, pear, hazelnut, pistachio, walnut, plum, pomegranate, cherry, avocado, mango, and raspberry, and the severity of periodicity varies depending on the cultivar. For example, olive, pistachio, and hazelnut exhibit absolute periodicity, while the ‘Hüryemez’ apple cultivar exhibits partial periodicity. Similarly, while the severity of periodicity is weak in the ‘Domat’ cultivar of olive, it is very high in the ‘İzmir Sofralık,’ ‘Çakır,’ and ‘Memecik’ cultivars. Severe periodicity is observed in the ‘Yavuz 1’ cultivar of walnut, whereas the severity is low in the ‘Chandler’ cultivar. While periodicity is not observed in the ‘Washington Navel’ orange cultivar, its severity is quite high in the ‘Yafa 45’ and ‘Valencia Late’ cultivars. The severity of periodicity observed in the ‘Çakıldak’ and ‘Acı’ cultivars of hazelnut is very strong, while it is moderate in the ‘Tombul’ cultivar and weak in the ‘Foşa’ cultivar (Kunter & Güneş, 2022).

2.2. Why does periodicity occur in plants?

No definitive solution has been found for the problem of alternate bearing (periodicity), which is an important issue in fruit cultivation; however, various explanations have been proposed regarding the causes of periodicity. Among these explanations, the most emphasized factors are the nutritional status of the tree in the on-year, the carbohydrate/nitrogen (C/N) balance, and endogenous hormones. The basis of these explanations is that due to the heavy crop load in the on-year, flower buds fail to form as a result of inadequate nutrient supply. Bud formation fails to occur because the tree does not contain sufficient nutrients (especially P, N, Zn, B, and Mn), leading to the failure of bud break (Serdar, 2025).

Additionally, seedless fruit formation resulting from boron deficiency, problems related to orchard establishment (such as insufficient or non-uniform light exposure of trees and inhibited bud formation due to inadequate aeration), meteorological events such as frost, poor quality of irrigation water and insufficient irrigation are listed as major factors causing periodicity. At the same time, adverse environmental conditions (drought, salinity, etc.) may disrupt nutrient uptake and hinder tree growth. Furthermore, when the electrical conductivity (EC) value of water sources exceeds the plant’s tolerance threshold and when saline groundwater or irrigation water is used, the development of the plant can be negatively affected. Because this creates salinity stress in the plant, it may lead to reduced vegetative growth and fruit formation in fruit trees. Moreover, the fruits developing on the tree are major consumers of nutrients absorbed by the roots, and therefore, the excessive fruit load has a high likelihood of disrupting the mineral balance within the tree. The availability of nutrients—which is a prerequisite for the growth performance of the plant—is largely determined by the plant's internal ability to access and use nutrients in a timely manner according to the seasonal supply–demand balance within the tree.

A tree that exhibits periodicity expends more nutrients and energy during the on-year because it carries a heavy fruit load and must allocate resources to enlarge and ripen its fruits; therefore, it cannot store sufficient nutrients for winter dormancy. For this reason, the tree enters winter dormancy/rest later in an attempt to compensate for the nutrient deficit. As a result, the tree becomes susceptible to early autumn frosts and severe winter cold damage. After harvest, as winter approaches and the plant prepares to enter dormancy, the uptake of nutrients from the soil slows down and decreases. Consequently, when the tree awakens from dormancy in the following year, adequate amounts of nutrients required for root development and flowering are not available within the tree's reserves. This severe deficiency in nutrient reserves prevents sufficient vegetative growth, development, and fruit formation in the plant, and this situation directly leads to the occurrence of periodicity in plants (Özcan, 2020).

In a study conducted by Ivanami et al. (2018), the effect of fruit thinning on periodicity in apple (Malus domestica) was investigated. In the study, heavily fruit-loaded apple trees in the "on-year" were thinned, and the development of fruits in the same season as well as the flower formation and fruit development in the following year were observed. The progression of these observations is also shown in Figure 1 by Campbell and Kalcsits (2024). As seen in Figure 1, when the high fruit load formed in the on-year was not subjected to thinning, the fruits remained small in size, and very low levels of flower formation occurred the following year, resulting in a small number of fruits. This process leads to alternate bearing every two years due to the physiological state of the tree. In contrast, thinning the fruits while they were still small allowed control of the fruit load on the tree, ensuring both the development of fruits with standard size and quality and the formation of healthy flowers in the following year, thereby enabling balanced yield without year alternation.

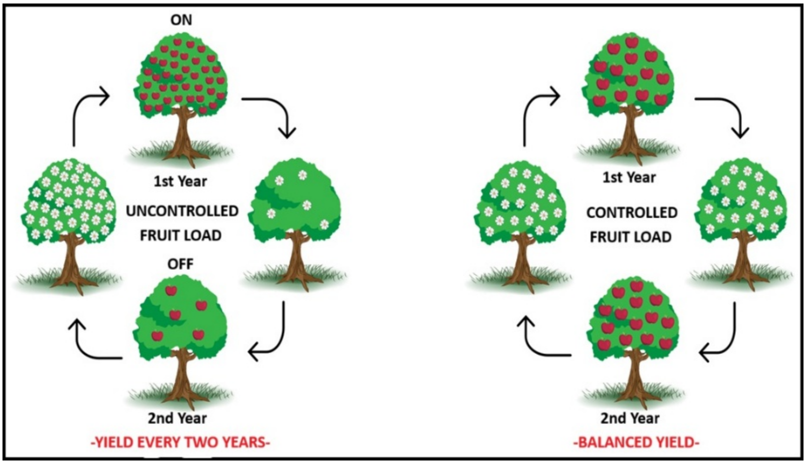

Figure 1. Effect of fruit load on flowering in apple trees (Campbell & Kalcsits, 2024).

2.3. Why is bud formation important in fruıt trees?

The formation of fruit buds/floral buds in fruit trees is a physiological process that forms the basis of productivity and regular crop production. Fruit buds are the buds that will form the flowers—and consequently the fruits—of the following year. Therefore, fruit bud differentiation (flower bud formation) plays a decisive role in the regulation of periodicity (on/off years), yield, and fruit quality in fruit trees. Fruit bud formation occurs one year in advance; thus, the yield potential of trees for the following year is determined by the growing conditions of the current year. For this reason, when fruit bud formation is insufficient, periodicity—namely the tendency to bear a heavy crop one year and a light crop the next—emerges. In the competition for nutrient use between the fruit, the fruit bud, and the leaf, the fruit dominates, and because the buds and leaves are not adequately nourished, they drop, forming the basis of periodicity (Serdar, 2025).

As the number of flowers formed in fruit trees increases, the fruit set rate may also increase in parallel with this situation. Deficiencies in certain nutrients or hormones may cause buds to enter dormancy; however, this condition can be alleviated and the flowering process supported through appropriate plant nutrient supplementation. The mechanism of flower bud formation and flowering may differ physiologically and biochemically depending on the fruit species (Awasthi ve ark., 2024).

2.4. How is fruit bud formation achieved in trees?

To ensure bud formation in trees—that is, to prevent periodicity—proper plant nutrition must first be provided. The most important element in this regard is Phosphorus (P). In addition, Nitrogen (N), Boron (B), Zinc (Zn), and Manganese (Mn) are the primary plant nutrients for bud formation. This is because these five nutrients are elements involved in protein synthesis. The occurrence of protein synthesis enables cell division, which in turn ensures bud formation in the tree. The nutrient that forms the bud is Zn, while the nutrients that fill the interior of the bud are P, N, B, and Mn. Through cell division, the interior of the buds becomes filled, and fruit buds are prepared. These processes affect the formation of buds for the following year (Serdar, 2025).

The effects of these five nutrients influencing bud formation on the plant are explained in detail below.

2.4.1. Phosphorus (P)

Phosphorus is a critical macronutrient that plays a direct role in fundamental physiological processes in plants, such as energy transfer, root development, flowering, and yield increase. At low temperatures, the availability and uptake of phosphorus by the roots decrease; furthermore, the pH range at which phosphorus exhibits maximum availability in soil is stated to be 6–7 (Kacar & Katkat, 2015).

Phosphorus deficiency in fruit trees leads to significant physiological disorders such as weakened root development, reduced shoot and bud formation, delayed flowering, and decreased quality. Furthermore, seed and fruit quality are negatively affected, and the ripening process is delayed. Therefore, phosphorus is reported to be one of the most important nutrients affecting periodicity in fruit trees (Kacar & Katkat, 2015).

In their study investigating the effect of phosphorus fertilization on yield and periodicity in olive (Olea europaea), Haberman et al. (2021) reported that phosphorus fertilization had no effect on vegetative growth; however, it significantly increased bud formation, flowering density, and fruit set rate. Furthermore, they reported that the none phosphorus fertilization in the off-year increased the severity of periodicity; while sufficient phosphorus fertilization in the on-year could alleviate periodicity by preserving the bud/flower potential for the following year due to the high fruit load. Therefore, they suggested that phosphorus may play a role in reducing periodicity, particularly in fruit trees suffering from phosphorus deficiency: sufficient phosphorus application after the on-year can support bud (flower) formation and soften the periodicity cycle.

2.4.2. Nitrogen (N)

Nitrogen is the nutrient element that plants absorb from the soil in the greatest quantity. Plants primarily take up nitrogen from the soil in the forms of nitrate (NO_3^-) and ammonium (NH_4^+) ions. Small molecular-weight organic nitrogen compounds can also be taken up by plant roots. Plants can directly absorb urea nitrogen into their systems. However, for urea to become more readily utilizable by plants, it must be decomposed and converted into ammonium and nitrate. Considering the time required for this process, urea application must be carried out earlier than other nitrogen fertilizers. Urea has height-promoting and root-developing effects in plants. It also influences fruit and grain development (Mengel et al., 2001). Nitrogen is a component of many important organic compounds in plants; proteins, amino acids, nucleic acids, enzymes, chlorophyll, ATP and ADP are important organic compounds that contain nitrogen. Therefore, nitrogen is required for the formation of new cells in the plant (Mengel et al., 2001).

Nitrogen deficiency causes stunted growth in plants, smaller leaves, chlorosis and premature shedding in older leaves; capillary root development weakens, and premature aging occurs in plants because N deficiency affects cytokinin synthesis (Mengel et al., 2001). In fruit trees, it is stated that the nitrogen content after harvest decreases significantly in years with high fruit load, therefore nitrogen applications in autumn and early spring are critically important for flowering and yield. On the other hand, excessive nitrogen applications also lead to negative consequences; excessive vegetative growth reduces grain and fruit yield, increases the sensitivity of plants to water stress, and delays harvest, leading to quality problems (Brohi et al., 1994).

2.4.3. Zinc (Zn)

High $CaCO_3$ (calcium carbonate), high pH, low organic matter content, insufficient microbial activity, and high clay content in the soil inhibit zinc uptake by plants. Under zinc deficiency, the chlorophyll content of plants decreases drastically, and photosynthesis declines. Zn ensures auxin hormone activity in the plant; when deficient, auxin activity decreases (auxin hormone is effective in plant elongation, tropic responses, and fruit ripening). Because auxin activity decreases, dwarfing occurs in plants. The number of buds decreases, and some buds remain unopened. Shoots die and leaves fall prematurely. In fruit trees, leaf formation is negatively affected. Rosette formation is observed at shoot tips. In addition, leaves cluster at the ends of branches and do not form in the lower parts, resulting in “whip-like” growth. (Mengel et al., 2001).

It is also known that excessive phosphorous fertilization causes Zn deficiency. High phosphate concentration creates metabolic disorder in the plant, leading to Zn deficiency. Zinc toxicity also occurs in plants. Toxicity is mostly seen near zinc mineral deposits and reduces root development of the plant. In addition, the uptake of P and Fe by the plant decreases (Mengel et al., 2001).

2.4.4. Boron (B)

Among micronutrients, boron is the only non-metal element. In soils of humid regions, since it is not found in ionic form, it does not bind to soil colloids and is easily leached. An important portion of plant-available boron in the soil is bound to soil organic matter. Excess P in the soil adversely affects the uptake and transport of B in the plant. High Ca levels in the soil help reduce B toxicity, but at the same time negatively affect P precipitation and its uptake by plants (Kacar & Katkat, 2015)..

Under B deficiency, branches become brittle (insufficient lignification), and flower and fruit formation are inhibited (fertilization deficiencies). Fruit and flower drop, problems in pollen germination and pollen tube development, shortened internodes, and bushy growth occur, and fruit deformities develop. Since deficiency primarily damages the plant's growing points, growth slows down, and in severe deficiency conditions, death of the growing points occurs. Furthermore, under boron deficiency, the synthesis of cytokinins (plant hormones) decreases, while auxin accumulation increases. The necrosis observed at the growing points of boron-deficient plants (formation of dry, dead tissue due to cell death) results from this auxin accumulation (Kacar & Katkat, 2015).

Boron toxicity may occur in soils of arid and semi-arid regions. The boron content of irrigation water is particularly important. The presence of 1 ppm boron in irrigation water causes damage in sensitive plants, and 10 ppm causes damage even in tolerant plant species. The major plant species most sensitive to boron toxicity include peach, grapevine, fig, walnut, apple, cherry, pear, apricot, orange, lemon, grapefruit, and avocado (Yurtseven, 2017).

2.4.5. Manganese (Mn)

Manganese is generally known as immobile element in the plant. Plants absorb manganese in the form of Mn^{2+}. Mn uptake is in competition with other cations (Mg, Ca, Zn, Fe). Due to its chemical behavior, Mn^{2+} resembles both alkaline earth cations such as Mg^{2+} and Ca^{2+} and heavy metals such as Fe^{2+} and Zn^{2+}. Therefore, all of these cations negatively affect Mn uptake and transport within the plant. Magnesium, in particular, reduces Mn uptake. In soils where liming has been applied, Mn uptake decreases due to both the antagonistic effect of Ca^{2+} ions and the reduced solubility of Mn resulting from increased soil pH. In plants suffering from manganese deficiency, cell size decreases and flowering is delayed (Kacar & Katkat, 2015).

High soil pH is the main cause of manganese deficiency. In acidic soils, available Mn is quite high due to the solubility of Mn compounds. High soil pH also encourages manganese to form complex compounds with soil organic matter, thus reducing Mn availability. Mn deficiency can occur in plants grown in soils with high pH and rich organic matter. In high-pH, calcareous soils, selecting acidic fertilizers for microelement fertilization can have a positive effect on plant Mn uptake. Furthermore, manganese plays a role in the breakdown of water in photosynthesis. Therefore, Mn regulates the water economy of the plant (Kacar & Katkat, 2015).

In conclusion, these five plant nutrients (P, N, B, Zn, and Mn), described in detail above, have direct effects on shoot growth as well as on bud, flower, and fruit formation. Therefore, to prevent inadequate cell division and insufficient bud formation—which are factors leading to biennial bearing—careful application of these plant nutrients is considered extremely important in reducing and preventing the effects of biennial bearing.

There are also other plant nutrition techniques to minimize and overcome the consequences of biennial bearing. For example, the few fruits formed in an “off year” of a fruit tree are generally larger in size. The cell wall of these enlarging fruits must be strengthened. Since fruits with weak cell walls are prone to cracking, they also become susceptible to diseases and pests. This results in yield and quality losses. The nutrient element directly responsible for strengthening the cell wall is calcium (Ca) (Mengel et al., 2001). Fruit-bearing plants are more severely affected by chlorosis caused by iron (Fe) deficiency (e.g., strawberry, grapevine, citrus, kiwifruit, apricot, peach, cherry, pear). Chlorosis begins in the leaves and may also appear in the fruits, leading to economic losses. Iron uptake occurs mostly in the active root tips of the plant. Therefore, root health and root quality are extremely important for the uptake of nutrient elements (Mengel et al., 2001).

Along with these nutrients, there are also liquid organic fertilizers and hormones applied to plants that regulate plant development and support fruit set/bud formation. The most commonly used among these are listed below:

- Amino acids: They contribute to the development of roots, stems, leaves, flowers, and fruits, and play a role in the transport of nutrients from the roots to the relevant organs.
- Seaweed extract: The nutrients it contains support cell development in the plant's roots and stems.
- Auxin: It promotes root and stem development and is effective in flower formation and fruit set in plants. It also prevents leaf shedding.
- Cytokinin: It supports cell division and helps plant tissues remain young. It is also present and utilized in growing and developing plant tissues.
- Gibberellin: While it supports vegetative growth, it also affects flowering, fruit growth, and maturation. Auxin, cytokinin, and gibberellin hormones are naturally occurring and synthesized within the plant. However, the levels of these hormones synthesized by the plant itself may sometimes be insufficient. In such cases, these hormones are used as supplements (Kumlay & Eryiğit, 2011).

3. SOME STUDIES ON PERIODICITY

Bustan et al. (2013) analyzed the relationship between fruit load and macro-element dynamics in olive trees (Olea europaea L.) by comparing high-yielding and alternate-bearing trees. In the on-year, high-yielding trees produced 124.5 kg $tree^{-1}$, whereas alternate-bearing trees yielded only 7.4 kg $tree^{-1}$; in the off-year, yields declined to 106.4 kg $tree^{-1}$ and increased to 30.6 kg $tree^{-1}$, respectively, indicating that excessive crop load intensified yield fluctuations. Under arid and saline conditions, applied nutrients were largely stored within the plant, with N, P, and Ca accumulating in vegetative organs and K in fruits. Although these nutrients did not directly affect current yield, they supported subsequent vegetative growth and flowering. The study concluded that alternate bearing in olive primarily results from inadequate vegetative growth and weak bud induction during the on-year, highlighting the importance of balanced fertilization adjusted to crop load.

Choi et al. (2010) examined the effect of fruit load on nutrient distribution in 3-year-old Fuyu persimmon (Diospyros kaki L.) trees by adjusting leaf-to-fruit ratios (10–60) under uniform cultural practices. Increasing the leaf-to-fruit ratio markedly reduced nutrient accumulation in fruits; at a ratio of 60, fruits contained 17% of total N, 32% of P, and 28% of K, whereas at a ratio of 10 these values increased to 44%, 81%, and 74%, respectively. These results indicate that fruit load strongly regulates nutrient partitioning within the tree. Low leaf-to-fruit ratios favored nutrient allocation to fruits, promoting high yield but limiting reserve accumulation, while higher ratios enhanced nutrient storage in vegetative tissues, supporting flower bud formation and reducing the severity of alternate bearing.

Gündeşli et al. (2021) examined seasonal changes in mineral nutrient composition of shoots and leaves in pistachio

(Pistacia vera L. cv. “Uzun”) during on- and off-years over a two-year period (2015–2016), focusing on alternate bearing and flower abscission. In the on-year, leaf concentrations of P, K, Ca, Mg, Fe, Zn, Mn, and B and shoot concentrations of N, K, Mg, Ca, Zn, and Cu were higher. Nutrient levels of N, P, K, Mg, Zn, and Mn declined markedly during flower abscission and kernel development, indicating intense nutrient competition. Fruit presence significantly affected P, K, Mg, and Zn contents, while B decreased to deficient levels during flowering, suggesting a role in flower abscission. The study highlighted N, P, K, Ca, B, and Fe as key elements linking fruit load, nutrient dynamics, and yield.

Atay & Atay (2024) examined the relationship between fruit load and leaf nutrient composition in apple (Malus domestica cv. Golden Delicious/M.9) to clarify the nutritional basis of alternate bearing. The results showed that alternate bearing is largely driven by carbon- and nutrient-based source–sink balance. Leaf nitrogen (N) and copper (Cu) contents were not significantly related to fruit load, indicating an indirect role in alternate bearing. In contrast, calcium (Ca) and boron (B) responded strongly to fruit load. Leaf Ca increased with increasing fruit load due to its limited phloem mobility, whereas leaf B declined as fruit load increased because of its preferential translocation to fruits. Changes in leaf B were also associated with fruit skin color. Overall, Ca and B were identified as key indicators of source–sink imbalance underlying alternate bearing.

Stander et al. (2018) evaluated the relationship between leaf macro-nutrient status (N, P, K, Ca, and Mg) and alternate bearing in ‘Nadorcott’ mandarin (Citrus reticulata) over three seasons. On-year trees with high fruit load exhibited higher macro-nutrient concentrations and 2–7 fold greater nutrient export compared with off-years. However, leaf nutrient levels had no significant effect on shoot growth, flowering, or fruit load in the subsequent season, indicating that nutrient status was a consequence rather than a cause of alternate bearing. Foliar applications of N and K did not improve growth or flowering, while Ca showed only a weak association with current yield. The authors concluded that alternate bearing is primarily driven by the physiological effects of excessive fruit load, highlighting crop load regulation and shoot development as key management strategies.

Kumar et al. (2021) examined the role of vegetative growth in alternate bearing of mango (Mangifera indica L.) and showed that shoot physiological age is a key determinant of flowering. Irregular postharvest shoot development created asynchronous shoot ages, disrupting flowering uniformity and intensifying alternate bearing. In high-yield years, greater allocation of carbohydrates and nutrients to fruits limited vegetative growth and reduced reserve accumulation, weakening floral induction in the following season. The study emphasized that uniform and timely shoot development is critical for mitigating alternate bearing. Pruning, particularly tipping, was identified as an effective practice, as it synchronizes shoot growth, improves canopy structure, and promotes carbohydrate accumulation. The authors concluded that integrated management combining pruning, shoot physiology, and nutrition is essential for reducing alternate bearing and ensuring stable yields.

4. CONCLUSIONS

Periodicity is a complex physiological phenomenon in which multiple factors play a role, with numerous causes and great difficulty in prevention. Its impact on fruit crops cannot be underestimated or ignored, as it may lead to large-scale production, yield, quality, and economic problems—affecting not only growers whose livelihood depends on fruit cultivation, but also society and the national economy. Since this phenomenon does not occur only in a few plant species or specific regions, it constitutes a global issue and cannot be resolved with a definitive solution.

Selecting appropriate cultivars for each region and attempting to keep the tree under control by regulating crop load through pruning and thinning are important practices for reducing, and even preventing, the severity of alternate bearing; however, these measures alone are not sufficient. In order to ensure healthy, vigorous, resilient trees with proper bud formation, flowering, and fruit set, it is essential to address the nutrient requirements of the plant by considering the relationship between alternate bearing and plant nutrition. Nutrients supplied to the plant at the correct time must meet its needs and respond to urgent physiological demands. Only under such conditions can satisfactory flowering and fruit development be achieved. Alongside solid and liquid fertilizers and hormones applied in plant nutrition, the method and amount of irrigation also constitute highly important factors. When the plant’s water and nutrient requirements are adequately met, proper vegetative and generative growth can be ensured, the structure of the plant can be preserved, and this, in turn, enables the appropriate implementation of the other aforementioned practices.

Heavy crop load can lead to weakened vegetative growth in many species. This may manifest as a reduction in the number of flowers, a decrease in fruit set rate, or an increase in fruit drop. Environmental conditions also influence this balance; for instance, inadequate flowering conditions or excessive fruit formation may cause the plant to naturally limit the number of fruits. The grower, however, can apply suitable horticultural practices to maintain the physiological balance of the tree. In this context, balanced pruning, flower and fruit thinning, and the use of growth regulators may improve the yield and quality of the crop.

The causes of alternate bearing—a global problem in fruit production—have been demonstrated through theoretical–practical knowledge and previous research to be manageable using the effective methods described. In particular, the direct role, functions, importance, and impact of plant nutrition practices on alternate bearing are indisputable.

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USE OF BIOSTIMULANTS IN AGRICULTURAL PRODUCTION

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1. INTRODUCTION

The rapid increase in the world's population has led to a parallel rise in demand for agricultural production, making food security and sustainable agricultural practices a top global priority. Over the past century, the intensive use of chemical fertilizers and pesticides has significantly increased to meet this growing demand for higher yields. However, such practices have disrupted soil ecosystem balance, causing adverse changes in the physical, chemical, and biological properties of soils. This deterioration in soil fertility negatively affects not only crop yield but also produce quality.In line with the contemporary paradigm of sustainable production, there is now a clear necessity to reduce chemical inputs and promote environmentally friendly, biologically derived practices in plant production (Calvo et al. 2014). Consequently, biostimulants-substances and microorganisms that protect soil health, support ecological balance, and enhance plant growth and resilience have gained remarkable attention and become a major focus of interest in modern agriculture as a promising tool to meet the demand for agricultural products in a sustainable manner.

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Biostimulants are defined as naturally derived substances or microorganisms that enhance plant growth, development, yield and stress tolerance, rather than acting primarily by supplying nutrient elements, but instead by regulating plant metabolism. Some researchers have further described biostimulants as agents that promote plant growth and development by increasing the uptake and use efficiency of water and mineral nutrients, while simultaneously strengthening the plant immune system and improving tolerance to abiotic stresses. They emphasise that these products are free of synthetic chemicals and contain natural organic acids, hormones and other bioactive compounds (Yakhin et al., 2017). Biostimulants are formulated with compounds capable of stimulating physiological and biochemical processes that help plants adapt to adverse environmental conditions, they have become agronomic products of considerable importance in modern agriculture. When biostimulants are applied concurrently with optimal doses of chemical fertilisers, they can achieve high yield levels together with superior harvest quality.

In this section, in addition to general information on biostimulants – whose importance in agricultural production has been rising steadily in recent years – detailed knowledge is provided regarding their effects on plant growth and development, stress tolerance, yield, and produce quality.

2. DEFINITION OF THE BIOSTIMULANT CONCEPT AND ITS IMPORTANCE IN TERMS OF AGRICULTURAL SUSTAINABILITY

Although chemical fertilisers, which have been widely used in agricultural production for many years, provide high yields in the short term, in the long term they lead to deterioration of soil structure, reduction of microbial activity and increased environmental pollution. In this context, reducing the use of chemical fertilisers and shifting towards environmentally friendly practices have become one of the fundamental objectives of modern agriculture. Consequently, in recent years biostimulants which support plant growth and enhance resilience against environmental stresses have begun to stand out as complementary inputs in crop production in order to ensure the sustainability of agriculture (Calvo et al., 2014).

Biostimulants have been defined as materials that are applied to plants foliarly, via soil, or to seeds with the aim of positively influencing plant development, nutrient uptake, produce quality and yield, as well as increasing plant tolerance to stress; they may contain organic or inorganic compounds and/or microorganisms, and some of them also exhibit soil-structure-improving effects (Yakhin et al., 2017).

Biostimulants are not fertilisers; therefore, they do not directly supply the nutrient elements required by the plant. However, by promoting root development and regulating enzymatic activities, they enable more efficient and effective utilisation of the plant nutrients supplied through chemical fertilisers. Biostimulants are capable of reducing the fertiliser requirement of plants while simultaneously increasing yield and quality. Numerous studies have demonstrated the positive responses of various crop species to biostimulant applications (Gürsoy, 2022).

Compared to chemical fertilisers, biostimulants exhibit lower environmental impact, higher biological efficacy and greater potential for sustainable production. Moreover, their regular use contributes to the rebalancing of soil microbial populations and to the long-term preservation of soil health. Consequently, biostimulants stand out as environmentally friendly biotechnological solutions that support the reduction of chemical inputs in agricultural production while activating the plant's natural defence and nutrient-acquisition mechanisms. For this reason, the use of biostimulants is regarded as a fundamental tool in the development of sustainable agricultural systems (Rouphael & Colla, 2020).

3. PRODUCTION AND CONSUMPTION OF BIOSTIMULANTS WORLDWIDE AND IN TÜRKİYE

The global biostimulant sector is experiencing rapid growth, supported by strong research and development infrastructure and favourable regulatory frameworks. In Europe, products are required to be backed by efficacy trials and scientific evidence, and specific performance criteria must be met for a product to be officially recognised as a "biostimulant". At the global level, the biostimulant market was projected to reach USD 2.91 billion between 2016 and 2021, growing at an annual rate of 10.4% (Külahtaş and Çokuysal, 2016). The industry is predominantly concentrated in the Americas and Europe.

In Türkiye, the biostimulant market is still in its development phase. Biostimulants have been officially authorised for use in the country since 2002 (Külahtaş and Çokuysal, 2016). Although domestic production is steadily increasing, many companies continue to rely on imported raw materials. However, this dependency is changing rapidly; significant domestic advances are being made, particularly in the production of leonardite-derived humic acids, seaweed-based extracts, and microbial formulations.

In 2024, the North American market accounts for 27.9% of the global biostimulant market share. The United States holds a dominant position in the North American biostimulant market and demonstrates strong growth potential. The Latin American biostimulant market holds a 10.2% market share in 2024 and is expected to exhibit robust growth in the forthcoming period. The Middle East and Africa market accounts for a 3.9% share in 2024 and is showing positive growth trends (Anonymous, 2025).In our country, however, due to the market still being in its developmental stage, no reliable, up-to-date market share data could be obtained.

In conclusion, the global biostimulant market is expanding rapidly, driven primarily by the growing need for sustainable agriculture, increasing consumer demand for organic products, stress factors associated with climate change, and rising investments in research and development.

4. FUNDAMENTAL DIFFERENCES BETWEEN FERTILISERS, PESTICIDES AND BIOSTIMULANTS

The main products used in crop production can be classified as fertilisers, pesticides and biostimulants, each differing significantly in purpose, mode of action and environmental impact.Fertilisers directly support plant nutrition by supplying the macro- and micronutrients essential for plant growth and development (Calvo et al., 2014).

Pesticides are used to control pathogens, insects or weeds that have harmful effects on plants. They generally act through toxic mechanisms that are lethal or inhibitory to the target organisms (Pimentel, 2005).

In contrast, biostimulants do not primarily supply nutrients to the plant; instead, they activate the plant’s own metabolic and physiological mechanisms. Biostimulants stimulate plant hormones, root and shoot development, photosynthetic capacity and antioxidant defence systems, thereby increasing stress tolerance, produce quality and yield (Du Jardin, 2015; Bulgari et al., 2019). Biostimulants are regarded as biological products that have minimal adverse effects on the environment and are highly suitable for sustainable production systems (Yakhin et al., 2017). Consequently, whereas fertilisers provide nutrient support and pesticides control harmful organisms, biostimulants optimise yield and quality by activating the plant's intrinsic mechanisms. This distinctive mode of action has positioned biostimulants as a key component of modern, sustainable agriculture.

5. CLASSIFICATION OF BIOSTIMULANTS

Although various classification approaches exist for biostimulants, most researchers generally group them into the following major categories:seaweed extracts,humic substances (humic and fulvik acids),protein hydrolysates and amino acids of plant and animal origin,beneficial microorganisms,chitin, chitosan and other biopolymers(Calvo et al., 2014; Külahtaş & Çokuysal, 2016).On the other hand, proposed a slightly more detailed classification: Humic and fulvik acids,protein hydrolysates, amino acids and other nitrogen-containing compounds,seaweed extracts and botanical extracts,chitin- and chitosan-derived biopolymers,inorganic compounds,beneficial fungi,beneficial bacteria(Du Jardin ,2015). Kauffman et al. (2007) adopted a simpler system based on source and composition, dividing biostimulants into three main groups: humic substances, seaweed extracts, and amino acid-containing products.

5.1. Humic and fulvic acids

Humic substances are high-molecular-weight organic compounds formed through the long-term microbial decomposition (humification) of plant, animal and microbial residues. They constitute the most biologically active fraction of soil organic matter.

Recent studies have demonstrated that humic acids increase plant tolerance to abiotic stresses (salinity, drought, heavy metals, extreme temperatures) and enhance the use efficiency of nutrients such as nitrogen and potassium, thereby offering significant potential to reduce fertiliser requirements (Nardi et al., 2021; Ampong, 2022).

Due to their lower molecular weight, fulvic acids can more easily cross plant cell membranes. They have been reported to promote root development, stimulate enzyme activity, increase nutrient uptake, and improve photosynthetic efficiency and overall plant vigour (Zandonadi et al., 2007).

Among the humic and fulvic acid types most widely used in agriculture, those derived from leonardite rank first. The second most preferred group consists of humic substances originating from lignite and peat. Lignite is a type of organic coal in which the humification process is one step behind that of leonardite and which consequently contains lower proportions of humic acids. Peat, on the other hand, is a natural organic material formed by the partial decomposition of plant residues in wetland environments (Muscolo et al., 2013; Shah et al., 2018).

5.2. Seaweed (algal) extracts

Seaweed extracts are natural-origin biostimulants containing the biologically active compounds of macroalgae (seaweeds) that grow naturally in seas and oceans. These products are predominantly derived from brown (Phaeophyceae), green (Chlorophyceae) and red (Rhodophyceae) algal species.Numerous studies have demonstrated that seaweed extracts increase chlorophyll content and yield in a wide range of crops under both field and greenhouse conditions (Chen et al., 2021; Kisvarga et al., 2024).

5.3. Protein hydrolysates and amino acid-based biostimulants

Protein hydrolysates are biologically active organic mixtures obtained by hydrolysing plant- or animal-derived proteins into smaller building blocks, namely peptides and free amino acids.

The primary raw materials for protein hydrolysates consist of:plant-origin materials (soybean meal, wheat gluten, maize protein, legume seeds, algae) and animal-origin materials (fish by-products, leather meal, collagen, gelatin, feather meal, blood meal, etc.)These raw materials are processed by enzymatic, acidic or alkaline hydrolysis to produce extracts rich in amino acids and peptides.Protein hydrolysates positively affect plant growth and metabolic activity primarily by increasing nitrogen-use efficiency (Colla et al., 2015). Plant-derived protein hydrolysates produced by enzymatic hydrolysis have been shown to enhance photosynthetic activity and yield, particularly when applied foliarly (Ertani et al., 2009; Ertani et al., 2013). Most Commonly Used Protein Hydrolysates and Amino Acid-Based Biostimulants in Agriculture

5.4. Chitin and chitosan

Chitin is the second most abundant natural polysaccharide after cellulose and is a nitrogen-containing structural polysaccharide found in many organisms. It occurs naturally primarily in the exoskeletons of crustaceans (shrimp, crab, lobster), in fungal cell walls, in insect exoskeletons, and in certain algal species.

Chitosan, on the other hand, is a cationic (positively charged) biopolymer obtained by partial deacetylation of chitin (i.e., removal of acetyl groups). Due to their environmentally friendly nature, both chitin and chitosan are recognised as important biostimulant groups approved for use in organic agriculture.

Chitosan has been shown to activate induced defence mechanisms in plants, thereby increasing the production of phenolic compounds and phytoalexins (El Hadrami et al., 2010). In agricultural applications, chitosan exerts positive effects on parameters such as seed germination, root development, leaf growth, flowering, and yield (Sharif et al., 2018). The most common sources of chitin and chitosan used in agriculture are shrimp shells, crab shells, mixed shellfish waste, and fungal chitin (e.g., Aspergillus niger, Mucor rouxii).

Industrial chitosan production is currently predominantly derived from the chitin of marine crustaceans, which represents the most abundant and economically viable source of chitin worldwide (Kumar, 2000). Chitin/chitosan obtained from shrimp shells is particularly preferred in agricultural biostimulant applications due to its high biocompatibility, elevated purity, and low toxicity (Aranaz et al., 2009).

5.5. Microbial-origin biostimulants

Microbial-origin biostimulants are biological products that either contain live microorganisms (e.g., bacteria, fungi, actinomycetes, algae, etc.) or are derived from the metabolites of these organisms. They offer a sustainable approach to increasing yield and quality in agricultural systems by promoting plant growth (Sible et al., 2021).

The origin of microbial biostimulants dates back to the discovery of beneficial microorganisms in nature. Research in agricultural microbiology, particularly from the mid-20th century onward, revealed that certain beneficial bacteria living in the plant rhizosphere (e.g., *Azospirillum*, *Bacillus*, *Pseudomonas*, *Rhizobium*) directly influence plant growth, which significantly increased interest in these organisms. Initially, these microorganisms were evaluated solely as biofertilisers; however, today their biostimulant effects, rather than direct nutrient supply, have come to the forefront. Numerous studies have demonstrated the positive effects of microbial biostimulants on stress tolerance and nutrient-use efficiency (Backer et al., 2018). The main groups of microbial biostimulants are rhizobacteria that promote plant growth, mycorrhizal fungi (arbuscular mycorrhiza – AMF), Trichoderma species, endophytic microorganisms, and algae and cyanobacteria.

Microbial biostimulants are widely used in agriculture and are recognised as important groups that provide significant benefits to sustainable farming practices. In addition to the groups mentioned above, actinomycetes, yeasts, and various fermentation-derived products (e.g., microbial metabolites, bioeffectors, and compost teas) are also included among these valuable microbial biostimulant categories.

6. BENEFITS OF BIOSTIMULANTS TO PLANTS AND SOIL

Biostimulants promote growth by regulating physiological and biochemical processes in the plant while simultaneously exerting a positive influence on the biological activity of the soil ecosystem. In this respect, biostimulants represent key components of sustainable agricultural systems, offering benefits both to plant physiology and to soil microbiology.

6.1. Benefits to plants

The effects of biostimulants on plants primarily manifest as the regulation of cellular metabolism, stimulation of the synthesis of growth-regulating compounds, and enhancement of resilience to stress conditions. Additional specific benefits are detailed below.

6.1.1. Promotion of root development

Biostimulants stimulate root system development, particularly by inducing the production of auxin-like compounds. A well-developed root system facilitates the plant's access to water and uptake of water and nutrient elements. The increase in root surface area also contributes to elevated microbial activity in the rhizosphere and accelerates nutrient cycling (Calvo et al., 2014).

6.1.2. Enhanced nutrient uptake and use efficiency

Microbial biostimulants, particularly species such as *Azospirillum*, *Bacillus* and *Pseudomonas*, increase the availability of nutrient elements to plants through mechanisms including solubilisation of phosphorus, biological nitrogen fixation, and chelation of micronutrients. This markedly improves plant nutrition, especially in low-fertility soils, and reduces the need for chemical fertiliser inputs (Rouphael & Colla, 2018).

6.1.3. Increased photosynthetic activity and chlorophyll synthesis

Biostimulant applications activate enzymes involved in chlorophyll biosynthesis, thereby enhancing overall photosynthetic capacity. The resulting increase in chlorophyll content elevates the rate of carbon fixation and, consequently, biomass accumulation. This effect is particularly pronounced with organic biostimulants such as seaweed extracts, amino acids and humic substances (Ertani et al., 2012).

6.1.4. Improved tolerance to abiotic stresses

Under stress conditions such as drought, salinity, extreme temperatures or cold, biostimulants activate antioxidant defence systems in plants. They increase the activity of key protective enzymes including superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD), thereby reducing oxidative cellular damage. Additionally, they help maintain osmotic balance, limit water loss, and enhance cell membrane stability (Colla et al., 2015).

6.1.5. Improvement of produce quality

Biostimulant applications exert particularly positive effects on quality parameters in vegetables and fruits. Numerous studies have demonstrated that biostimulants increase fruit sugar content, ascorbic acid levels, phenolic compound concentrations, and pigment content (anthocyanins, lycopene, carotenoids, etc.) (Kocira et al., 2020).

6.1.6. Enhanced flowering and fruit set

Biostimulants that stimulate the production of plant growth-regulating hormones (IAA, gibberellins, cytokinins) regulate the flowering period and improve pollen viability. This leads to higher fruit-set rates and, consequently, increased yield (Du Jardin, 2015).

6.2. Benefits to soil

The effects of biostimulants on soil can be summarised as increasing microbial community activity, enriching organic matter, and improving soil structure. These effects support long-term soil fertility and sustainability.

6.2.1. Increase in microbial activity

Microbial-origin biostimulants increase the populations of beneficial microorganisms (e.g., *Trichoderma*, *Bacillus*, *Pseudomonas*), thereby helping to maintain the biological equilibrium of the soil ecosystem. These microorganisms compete with pathogens, reduce disease pressure, and accelerate the mineralisation of organic matter (Bhattacharyya & Jha, 2012).

6.2.2. Improvement of soil structure and physical properties

Organic-origin biostimulants (humic and fulvic acids, seaweed extracts, etc.) enhance aggregate stability and structural integrity. This improves water-holding capacity, infiltration rate and aeration, creating a more favourable environment for root development (Canellas & Olivares, 2014).

6.2.3. Increased availability of nutrient elements

Humic and fulvic substances form complexes with metal ions, thereby facilitating plant uptake of micronutrients (Fe, Zn, Mn, Cu). They also solubilise phosphorus, making it more available to plants. These properties are particularly enhance nutrient efficiency in neutral and alkaline soils (Zandonadi et al., 2010).

6.2.4. Elevation of soil organic matter content

Regular use of organic biostimulants raises soil organic carbon levels and promotes humus formation. The increased organic matter stimulates soil microbial activity and contributes to the long-term preservation of soil fertility (Calvo et al., 2014).

6.2.5. Preservation of soil ecosystem biological balance

Biostimulants promote the development of beneficial microorganisms while suppressing harmful microflora and pathogens. This establishes biological balance in the soil and creates conditions suitable for sustainable production. Maintaining soil biological equilibrium is of critical importance for the development of sustainable agricultural systems, as biodiversity enhances the ecosystem’s resilience to stresses (Lehmann et al., 2020).

7. APPLICATION METHODS OF BIOSTIMULANTS

Biostimulants can be applied in different ways depending on their composition, formulation, targeted effect, and the plant's developmental stage. The correct choice of application method directly influences the plant's uptake efficiency and the overall effectiveness of the biostimulant.The most common application methods are: foliar application,soil application,seed / planting material treatment (seed coating, seedling dip, tuber treatment, etc.)These methods play a crucial role in enhancing plant growth, nutrient uptake, and stress tolerance (Calvo et al., 2014).

7.1. Foliar application

Foliar application is a method that allows biostimulants to penetrate directly into plant tissues, thereby providing rapid action. The main advantages of foliar application are fast absorption by the plant and direct incorporation of nutrients and organic compounds into metabolic activity.

Seaweed extracts (particularly due to their cytokinin and auxin content) and amino acid-based biostimulants are especially recommended for foliar application. Foliar use of amino acid- or protein hydrolysate-based biostimulants has been shown to increase yield and improve nutritional quality in greenhouse cultivation (Calvo et al., 2014).

7.2. Soil application

Soil application is a method that delivers biostimulants directly to the root zone, thereby promoting root development and nutrient uptake. The main advantages of soil application include long-term effects on root growth, rhizosphere microflora and soil structure, more efficient use of nutrient elements by the plant, and increases in soil pH and cation exchange capacity (CEC). Applying liquid biostimulants through fertigation systems significantly increases efficiency by providing direct access to the root zone (Rouphael & Colla, 2020).

The most effective biostimulant groups for soil application are humic and fulvic acids and microbial-origin biostimulants (PGPR, mycorrhizal fungi and *Trichoderma* spp.) (Du Jardin, 2015; Calvo et al., 2014).

Chitin and chitosan, which are included in biostimulant classifications, can be applied both soil-applied and foliar-applied.

7.3. Seed, seedling and planting material treatment

Application to seeds, seedlings or planting material (tubers, bulbs, cuttings, etc.) enables biostimulants ensures maximum effectiveness from the very beginning of the plant’s life cycle. The main advantages of this method are; accelerated and more uniform germination,higher seedling establishment and survival rates,significantly improved early-stage stress tolerance.

Biostimulants applied to seeds, seedlings or planting material are particularly effective in accelerating germination, enhancing seedling vigour and stimulating root development (El-Esawi et al., 2022; Calvo et al., 2014).

The biostimulant groups most suitable for seed/seedling treatment are;mycorrhizal fungi,nitrogen-fixing bacteria (e.g., *Azospirillum*, *Azotobacter*, *Rhizobium* spp.),protein hydrolysates and amino acid mixtures.

8. CONCLUSIONS

Biostimulants stand out as innovative and sustainable supportive products that offer effective solutions to some of the most critical challenges facing modern agricultural production systems, including yield losses, soil fatigue, climate change-induced stresses, and the ever-increasing demand for high-quality food.

When applied at the correct dose, timing and method, biostimulants provide multifaceted benefits such as improved produce quality, accelerated plant development, stronger root and shoot systems, increased nutrient uptake, and markedly higher resilience under stress conditions. At the same time, they contribute significantly to sustainable soil fertility by improving soil structure, boosting microbial activity, and supporting organic matter cycling.

Given the rising costs of agricultural inputs, mounting pressure from climate change, and the imperative of environmental sustainability, the importance of biostimulants continues to grow. Nevertheless, the rapid expansion of the biostimulant sector also highlights the need for further research in areas such as standardisation, regulatory frameworks, clearer elucidation of modes of action, and scientific validation of product performance across diverse plant–soil systems.

In conclusion, the wider adoption of biostimulants in agricultural production holds enormous potential for simultaneously enhancing productivity and sustainability. They serve as an important bridge that integrates traditional farming practices with modern agricultural paradigms. In the coming years, as scientific understanding deepens and the functional properties of these products become better characterised, the strategic significance of biostimulants in the agricultural sector is expected to become even more pronounced.

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TÜRKİYE VE DÜNYADA

TOPRAK BİLİMİ VE BİTKİ BESLEME

yaz

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