TÜRKİYE VE DÜNYADA BAHÇE BİTKİLERİ YETİŞTİRME VE ISLAHI

Editör: Doç.Dr. Sultan Filiz GÜÇLÜ

yaz
yayınları

Türkiye ve Dünyada
Bahçe Bitkileri Yetiştirme ve Islahı

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İÇİNDEKİLER

BATI AKDENİZ BÖLGESİ'NDE ÖRTÜALTI SEBZE YETİŞTİRİCİLİĞİNİN SON BEŞ YILLIK DEĞİŞİM

Halil DEMİR[1*]

Ömer ÖNEL[2]

1. GİRİŞ

Akdeniz Bölgesi, Batı Akdeniz ve Doğu Akdeniz diye iki alt bölgeye ayrılabilir. Batı Akdeniz Bölgesi içerisinde Antalya, Burdur ve Isparta illeri yer alır (Anonim 2025a). Bu bölge içerisinde kayıtlı yaklaşık 3.4 milyon kişi yaşamaktadır (Anonim 2025b). Bu bölgenin ekonomisi turizm ve tarıma dayalıdır.

Bu bölgede Akdeniz ikliminin özellikleri hakimdir. Genellikle yazları sıcak ve kurak, kışları ılık ve yağışlı geçmektedir. Kıyı bölgelerindeki yağış miktarı iç bölgelere göre daha yüksektir. Antalya için yaklaşık 785 mm/yıl, Burdur için ise yaklaşık 540 mm/yıl yağış değerleri verilmektedir. İklim özellikleri üzerinde denize yakınlık önemli şekilde etkili olmaktadır. Tarımsal üretimi de iklimsel özellikler etkilemektedir (Anonim 2025c).

Batı Akdeniz Bölgesi, Türkiye'nin tarımsal üretiminde önemli bir paya ve dolayısıyla önemli bir role sahiptir. Tarımsal üretim içerisinde narenciye (turunçgiller), elma, armut, ayva, muz, nar ve avokado gibi meyvelerin üretimi yoğun şekilde

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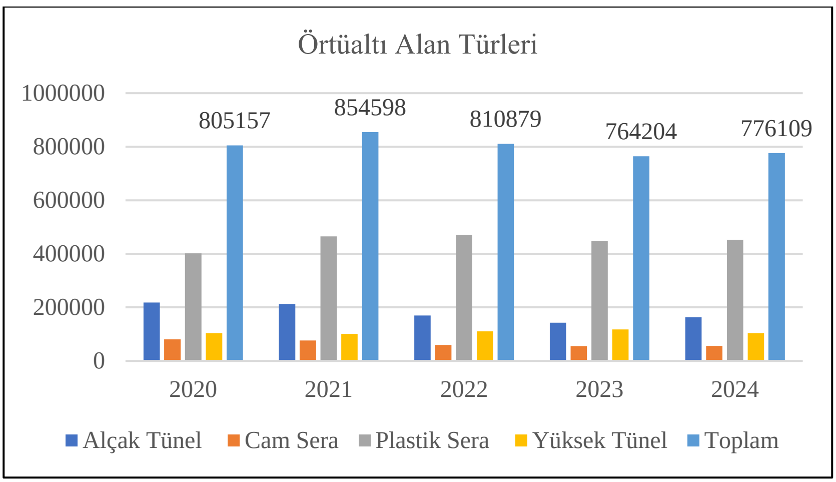
sürdürülürken, buğday, nohut, patates, şeker pancarı gibi tarla bitkileri üretimi de yapılmaktadır. Bu bölge içerisinde sebze üretimi de oldukça önemlidir ve örtüaltı sebzeciliği ekonomik döngüyü sürükleyen ayrı bir üretim kolunu oluşturmaktadır.

Örtüaltı kavramı seracılık kavramı ile çok sık karıştırılabilmektedir. Örtüaltında yapılan tarım; bazı bitkilerin, mevsimleri dışında, iklimsel bazı özelliklerin kısmen kontrol edilerek yetiştirilebilmesi şeklinde tanımlanabilir. Örtüaltı yetiştiriciliği alçak tüneller, yüksek tüneller, cam ve plastik seraları kapsayan alanlar içerisinde yapılan yetiştiriciliğe denilir (Tüzel vd. 2020). Buradan anlaşılacağı üzere örtüaltı kavramını sera ile karıştırmamak gerekir.

Örtüaltı sebze yetiştiriciliği, tarımsal üretim içerisinde en fazla istihdam sağlayan bir üretim koludur. Yaklaşık 60 yılı aşkın bir geçmişi olan örtüaltı yetiştiriciliği çok hızlı bir gelişme göstererek üretim ve ihracat açısından önemli bir konuma gelmiştir (Hızal ve Karlı 2020).

TÜİK (2025) verilerine göre, ülkemizdeki örtüaltı üretim alanlarının (da) son beş yıldaki değişimi Şekil 1'de gösterilmiştir.

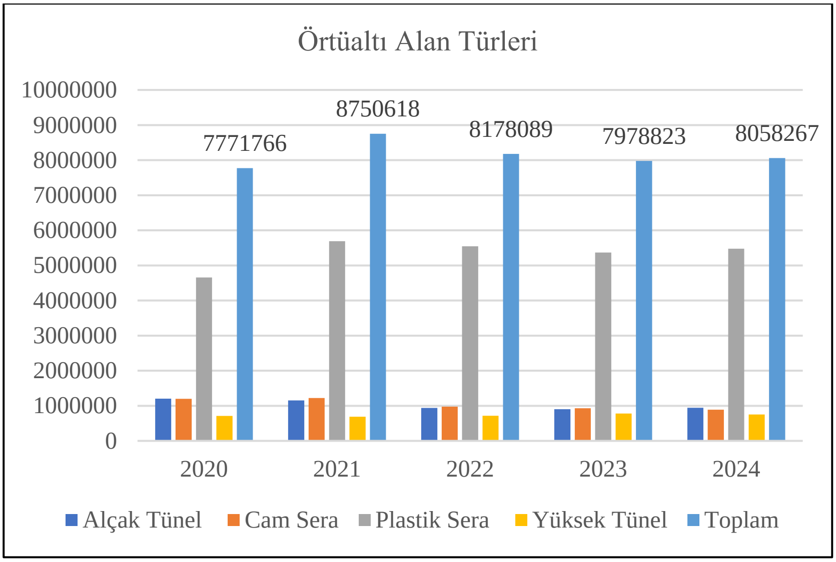


Şekil 1. Ülkemizin örtüaltı alanlarının son beş yıllık değişim değerleri

Toplam örtüaltı alanı 2020 yılında yaklaşık 805 bin da iken 2024 yılında yaklaşık 776 bin da'a ulaşmış durumdadır. Toplam alan miktarında az da olsa dalgalanmalar vardır. Ancak cam sera varlığı son beş yıl içerisinde sürekli azalma eğilimi göstermiştir. Cam sera alanlarımız 2020 yılında yaklaşık 81 bin dekardan 2024 yılında yaklaşık 56 bin dekara düşmüştür. Bu düşüşte hem sera kurulum maliyetleri hem de teknolojinin gelişmesiyle cam seraları aratmayan plastik sera konstrüksiyonları ve PE örtü malzemeleri etkili olmuştur. Ülkemizin alçak tünel varlığı 2020 yılına göre düşüş içinde olup 218 bin dekardan 163 bin dekara kadar gerilemiş durumdadır. Plastik sera alanlarımız ise artış eğilimindedir ve 401 bin dekardan 454 bin dekara ulaşmıştır. Yüksek tünel alanlarımız ise hemen hemen aynı kalmıştır.

Ülkemizin toplam sebze üretimi 2024 yılında 33.6 milyon ton olarak gerçekleşmiş ve bir önceki yıla göre %5.6 oranında artmıştır. Bu üretimin yaklaşık 8 milyon tonu ise örtüaltında yetiştirilen sebzelere aittir. Toplam sebze üretimi içerisinde de en fazla değer domatese ait iken, serada yapılan yetiştiricilikte de en fazla üretilen domatestir (TÜİK, 2025).

Örtüaltı alan türlerine göre sebze üretim miktarlarının (ton) son beş yıl içerisindeki değişimleri Şekil 2'de verilmiştir. Şekil'den de görüleceği gibi örtüaltı toplam sebze üretimi 2020-2024 yılları arasında az da olsa bir dalgalanma göstermiştir. Üretim miktarı 2020 yılında 7.7 milyon iken 2021 yılında bir milyon ton daha fazla üretim meydana gelmiş, daha sonraki yıllarda hafif düşüşlerle birlikte 2024 yılında 8.06 milyon tona ulaşmıştır. Cam sera alanlarındaki üretim miktarı, Şekil 1'de gösterilen alan düşüşüne paralel olarak düşme eğiliminde olmuştur.



Şekil 2. Örtüaltı alanlarındaki sebze üretim miktarlarının son beş yıldaki değişimleri

Alçak tünellerden elde edilen sebze miktarı 2020 yılında 1.2 milyon ton iken 2024 yılında 943 bin tona gerilemiştir. Plastik sera alanlarındaki artış, üretim miktarlarına yansımış durumdadır. Yaklaşık 4.7 milyon tondan 2024 yılındaki yaklaşık 5.5 milyon tona çıkmıştır. Yüksek tünel altında gerçekleştirilen sebze üretimi de 710 bin tondan 752 bin tona ulaşmış durumdadır.

Örtüaltı sebze üretim miktarı genellikle Akdeniz sahil şeridinde yoğunlaşmış olsa da son yıllarda rakımı yüksek bölgelerde örtüaltı alanları oluşturulmaktadır. Özellikle Antalya'nın Elmalı ve Korkuteli ilçelerinde olduğu gibi plastik sera alanları artmaya devam etmektedir (Adak vd. 2014). Batı Akdeniz Bölgesi'nin diğer illeri ve ilçelerinde de son yıllarda örtüaltı sebze üretiminde de gelişmeler yaşanmaktadır.

Bu bölümde, Batı Akdeniz Bölgesi'ne dahil olan başta Antalya olmak üzere Isparta ve Burdur illerinde yapılan örtüaltı sebze yetiştiriciliği değerlendirilecektir.

2. ANTALYA

Türkiye'de örtüaltı üretimi denilince ilk akla gelen şehirlerden birisi Antalya'dır. Bir tarım ve turizm şehri olan Antalya, özellikle serada yetiştiricilik ve seracılık sektörünün farklı kolları açısında son derece büyük öneme sahiptir. Fidecilik sektöründen sera kurulumu, topraksız tarım işletmelerinden gübre üretimine, tohumculuk sektöründen danışmanlık hizmetlerine kadar birçok farklı alt alanın merkezi konumundadır. Bu alt alanların oluşturduğu istihdam ve ekonomik yapı Antalya'ya güç katmaktadır.

Antalya'da sürdürülen örtüaltı sebze yetiştiriciliği üretim bölgelerinin özelliklerine göre farklılıklar gösterebilmektedir. Bu farklılıkları hem konstrüksiyon malzemesi, hem işletme tipleri hem de yetiştiricilik dönemlerinde görebilmekteyiz (Kılıç vd. 2020). Örneğin, Antalya'nın Kaş ilçesinin Kasaba, Dağbağ gibi üretim bölgelerinde en erkenci Sonbahar dönemi üretimine başlanırken, yakın üretim bölgeleri olan Kumluca ve Finike'de domates üretimine henüz başlanmamaktadır. Demre'de biber üretimi ön plana çıkarken Kumluca ve Finike'de domates, hıyar, biber ve patlıcan daha fazla üretilebilmektedir. Bu bölgelerde toptancı hali bulunduğundan dikenli hıyar, langa tipi hıyar, Macar tipi biber gibi ihracata yönelik sebzeler tercih edilebilmektedir.

Türkiye genelinde TÜİK (2025)'e göre toplam 776 110 dekarlık örtüaltı alanımız bulunmakta, bunların büyük bir bölümünde sebze üretimi yapılırken, bir kısmı da süs bitkileri ile meyve yetiştiriciliğinde değerlendirilmektedir. Antalya'nın toplam örtüaltı alanı içerisindeki payı yaklaşık %40.8 (316 957 da)'dir.

Toplam örtüaltı sebze üretimimiz 2024 yılında 8 058 187 ton olarak gerçekleşmiş, bu üretimin yaklaşık %52.1 (4 197 239 ton)'ini Antalya tek başına karşılamıştır. Yani Türkiye'de gerçekleşen örtüaltı sebze üretiminin yarıdan fazlası Antalya'ya aittir ve en fazla domates üretimi yapılmıştır. Biberler, patlıcan ve hıyar gibi sebzeler de en fazla üretilenler arasındadır.

Antalya topraksız tarım seralarıyla da dikkat çekmektedir. Ülkemiz genelinde topraksız tarım alanlarıyla ilgili resmi ve tek bir rakama henüz ulaşılamamaktadır. Yaklaşık 14 bin dekar alanda topraksız tarım yapıldığı bazı kaynaklarca bildirilmektedir (Anonim 2025d). Bu rakamın yaklaşık 15 bin dekara ulaştığını bildiren kaynaklar da mevcuttur. Ayrıca topraksız tarım işletmelerinin %19'u Antalya, %15'i Afyonkarahisar, %9'u İzmir, %6'sı Manisa ve %9'u Mersin'de bulunmaktadır (Anonim 2025d). TÜİK (2025)'e göre Antalya'nın ilçelerinin örtüaltı sebze yetiştiriciliği alanı (da) ve son beş yıllık değişimi Çizelge 1'de verilmiştir.

Çizelge 1. Antalya'nın ilçelerine göre örtüaltı sebze alan varlığı (da)

İlçeler	2020	2021	2022	2023	2024
Muratpaşa	2880	2878	6141	6141	6141
Konyaaltı	3057	3097	2008	2028	2084
Kepez	22722	22733	10723	15934	17404
Aksu	34140	74325	62436	60160	61245
Serik	48117	47058	48180	49010	49010
Manavgat	12812	13281	13637	13887	13987
Gündoğmuş	-	-	-	-	-
Akseki	9	9	9	9	9
Gazipaşa	22060	22230	26880	27300	24600
Alanya	19825	29355	28185	17630	17180
Korkuteli	9177	9702	6395	6750	6725
Elmalı	13462	12743	13667	14662	19855
Kemer	256	262	350	258	235
Kumluca	53904	52663	48717	48417	49057
Finike	6435	6604	6604	6604	6490
Demre	15918	16441	16424	16504	16772
Kaş	26800	28455	29940	29931	29931
Döşemealtı	128	129	114	198	206
İbradı	7	7	7	7	-

Çizelge 1'den de anlaşılacağı gibi Gündoğmuş ilçesinde herhangi bir örtüaltı alanı bulunmamaktadır. En az örtüaltı alana İbradı ve Akseki ilçeleri sahiptir. Son beş yıllık değişim incelendiğinde, 2020 yılında en fazla alan Kumluca ilçesinde iken zamanla az da olsa azalarak 2024 yılında yaklaşık 49 bin dekar olmuştur. Aksu'nun örtüaltı sebze alan varlığı 2020 yılında yaklaşık 34 bin dekar iken 2024 yılında alan miktarı 62 bin dekarı geçmiştir. Böylece en fazla alana Aksu ilçesi ulaşmıştır. Mevcut durumda en fazla örtüaltı sebze yetiştiriciliği Aksu, Kumluca ve Serik ilçelerinde yoğunlaşmıştır.

Ayrıca topraksız tarım seraları Serik, Kumluca ve Aksu ilçelerinde daha fazladır. Antalya'nın örtüaltı alan türlerine göre üretim alanı (da) ve üretim miktarlarının (ton) son beş yıllık değişimi Çizelge 2'de verilmiştir.

Çizelge 2. Antalya'nın örtüalatı alan türlerine göre üretim alanı ve üretim miktarı değişimleri

Yıllar	Değişim alanı	Alçak tünel	Cam sera	Plastik sera	Yüksek tünel
2020	Alan	9460	70219	205233	6797
	Üretim	5231	951220	2754208	46732
2021	Alan	8366	72434	254082	7090
	Üretim	43942	979436	3352539	56815
2022	Alan	7360	60568	247113	5916
	Üretim	41452	744289	3271593	51773
2023	Alan	7439	55914	241261	10816
	Üretim	41883	720701	3289819	108050
2024	Alan	7431	53755	248883	10862
	Üretim	41711	684897	3363386	107245

Antalya'da alçak tünel mevcudu son beş yıl içerisinde azalma eğiliminde olmuştur ve 2024 yılında alan miktarı 7431 da olarak kaydedilmiştir. Cam sera varlığının da alçak tünellerde olduğu gibi azalma eğiliminde olduğu görülmektedir. Hem cam sera hem de alçak tünel altındaki sebze üretiminde alandaki azalmaya paralel bir durum söz konusu olmuştur. Yüksek tünellerde hem alan hem de üretim miktarı son beş yıl içerisinde, dalgalanmalar olsa da artma eğiminde bulunmuştur. Plastik seralarda ise önemli bir artış söz konusudur. Alan ve üretim artışı 2020 yılına göre 2024 yılında yaklaşık %25 olarak gerçekleşmiştir.

TÜİK (2025) verileri incelendiğinde Antalya'daki sebze üretiminde domates, hıyar, patlıcan ve biber en fazla üretilen sebzeler arasında yer almıştır. Bazı üretim bölgelerinde seralar içerisinde marul, maydanoz gibi sebzelerin de üretildiği görülmekte, bunların özellikle imar geçirilip geçirilmeyeceği tartışılan Muratpaşa ilçesi gibi bölgelerde olduğu görülmektedir (Anonim 2025f). Serik ilçesinde ise son yıllarda birinci ürün olarak marulun yetiştirildiği, ikinci ürün olarak ise seralarda karpuz üretimine yer verildiği belirlenmiştir. Alçak ve yüksek tüneller daha çok Antalya'nın doğu ilçeleri olan Alanya, Gazipaşa ve Manavgat'ta olduğu tespit edilmiştir.

3. BURDUR

Batı Akdeniz Bölgesi'nde bulunan, Göller Bölgesi'nin önemli illerinden Burdur'un ekonomisi tarıma dayalıdır. Tarım sektörü içerisinde meyvecilik, hayvancılık ve son yıllardaki seracılık faaliyetleri üretime önemli katkılar sunmaktadır (Gül vd. 2021). Burdur'un ilçelerinin toplam örtüaltı üretim alanındaki son beş yıllık değişimi Çizelge 3'te gösterilmiştir. Çizelge 3'ten de görülebileceği gibi en az örtüaltı sebzecilik yapılan ilçeleri Kemer ve Yeşilova'dır.

Çizelge 3. Burdur'un ilçelerine göre örtüaltı alan varlığı

İlçeler	2020	2021	2022	2023	2024
Ağlasun	111	102	107	130	155
Altınyayla	193	190	190	180	186
Bucak	483	469	430	437	563
Çavdır	4603	5200	6000	6000	8200
Çeltikçi	735	765	740	790	790
Gölhisar	3402	3750	3950	3503	3631
Karamanlı	357	603	750	1100	1200
Kemer	-	-	-	-	11
Merkez	544	544	592	731	671
Tefenni	1408	1645	1662	1740	2430
Yeşilova	-	51	50	47	63

Son beş yıllık değişime dikkat edildiğinde Gölhisar, Çavdır ve Karamanlı dışındaki ilçelerdeki durumun hemen hemen aynı olduğunu söyleyebiliriz. Karamanlı ilçesindeki değişim 2020 yılına göre 2024 yılında dört kat artış şeklindedir ve toplam 1200 dekara çıkmıştır. En büyük örtüaltı sebze alanına sahip ilçe Çavdır'dır ve 2020 yılına göre kıyaslandığında yaklaşık %100'lük bir artış meydana gelmiş ve 8200 dekara ulaşmıştır. Çavdır ilçesindeki alanın büyük bir bölümünü plastik sera alanları oluşturmaktadır. Söğüt Kasabası Fethiye, Denizli ve Antalya yollarının kavşağındadır. Çevre bölgelerden hasat edilen sebzeler burada bulunan toptancı haline getirilir. Pazarlama sorunun daha az hissedildiği bu yörede seracılık hızla yaygınlaşmaktadır. İkinci en yüksek alan ise 3631 dekar ile Gölhisar ilçesindedir.

Burdur ilinin örtüaltı türlerine göre alan (da) ve üretim miktarlarındaki (ton) son beş yıllık değişim Çizelge 4'te sunulmuştur.

Çizelge 4. Burdur ilinin örtüaltı alan türlerine göre alan ve üretim miktarı değişimleri

Yıllar	Değişim alanı	Alçak tünel	Cam sera	Plastik sera	Yüksek tünel
2020	Alan	100	91	11637	8
	Üretim	176	840	186965	19
2021	Alan	95	91	13118	15
	Üretim	175	821	196860	34
2022	Alan	50	92	14305	24
	Üretim	87	840	236162	55
2023	Alan	53	95	14490	20
	Üretim	94	891	246595	44
2024	Alan	41	70	17752	37
	Üretim	71	575	291495	91

Çizelge'den de görülebileceği gibi en az üretim alanlarını sırasıyla yüksek tünel, alçak tünel ve cam seralar oluşturmaktadır. Alçak tünel ve cam sera varlıklarında azalmalarla birlikte yüksek tünellerde az da olsa bir artış mevcuttur. Ancak plastik sera varlığı son beş yıl içerisinde sürekli artış göstermiştir. Örtüaltı türlerine göre toplam alan miktarı da son beş yılda %50’den fazla artış eğiliminde olmuş, 2024 yılında toplam alan 17900 dekara ulaşmıştır. Üretim değerleri de alandaki değişime paralel seyretmiştir. Plastik sera alanlarından elde edilen üretim değeri yaklaşık %55 olarak gerçekleşmiştir. Toplam üretim miktarı 2024 yılında 292 232 tona ulaşmıştır. Burdur ili genelinde sera alanlarında en fazla üretilen sebze Gül vd. (2021) tarafından da belirtildiği gibi domates olup bunu hıyar izlemektedir.

4. ISPARTA

Göller Bölgesi’nin diğer önemli ili ise Isparta’dır. Isparta’yı Antalya’nın yayla kesimleri ile Burdur’dan ayıran özelliği kurulan seralarda süs bitkilerinin üretilmesidir. Isparta’da son beş yıl içerisinde örtüaltı alan varlığı az da olsa düşme eğilimindedir. Bu alanların önemli bir kesiminde süs bitkilerinin üretimi yapılmaktadır (Anonim 2025g). İl genelinde alçak tünel ve yüksek tünel bulunmamaktadır. 2020 yılında 85 dekar olan cam sera alanı 2024 yılında 19 dekara düşmüştür. Geri kalan alanın tamamı plastik seradır ve 2020 yılındaki 5293 dekarlık alan 2024 yılında 4927 dekara gerilemiştir. Bu alanın yaklaşık 1475 dekarında karanfil ve gül üretimi yapılmaktadır.

Isparta ilini sebzecilik açısından değerlendirmeye devam edersek, İlçelere göre toplam örtüaltı alan varlığı Çizelge 5’te gösterilmiştir. İlçeler arasında Yenişarbademli’de resmi verilere göre herhangi bir örtüaltı sebze üretimi görünmemektedir. Uluborlu ve Senirkent’te 2024 yılında sırasıyla 11 ve 18 da alan kurulmuştur. En fazla örtüaltı alan ise Yalvaç ve merkezde bulunmaktadır. Yalvaç’taki alan 2020 yılında 1612 dekar iken 2024 yılında 1113 dekara gerilemiştir. Isparta merkezdeki alan miktarı 2020 yılında 1735 da iken bu rakam 2024 yılında 1165 da düşmüş durumdadır. Toplam örtüaltı miktarı da 2020 yılından

2024 yılına kadar hafif dalgalı bir değişime sahip olmasına rağmen 3505 da'a kadar gerilemiştir.

Çizelge 5. Isparta'nın ilçelerine göre örtüaltı alan varlığı (da)

İlçeler	2020	2021	2022	2023	2024
Aksu	40	38	35	38	10
Atabey	330	290	300	320	370
Eğirdir	30	30	30	66	66
Gelendost	111	200	195	195	195
Gönen	71	57	57	40	40
Keçiborlu	14	14	14	13	13
Merkez	1735	770	765	1080	1165
Senirkent	-	-	-	-	18
Sütçüler	504	515	520	287	476
Şarkikaraağaç	60	20	20	10	28
Uluborlu	-	-	-	-	11
Yalvaç	1612	1612	1612	1280	1113
Yenişarbademli	-	-	-	-	-
Toplam	4507	3546	3548	3339	3505

Isparta genelinde örtüaltı türlerine göre sebze tarımının son beş yıllık değişimini Çizelge 6'da görebilirsiniz. İl genelindeki sebze üretimi yapılan cam sera varlığı 85 dekardan 19 dekara kadar gerilemiştir. Plastik sera alanları ise dalgalı bir gelişme seyri izlese de 2020 yılından 2024 yılına kadar toplamda %20'den fazla bir azalma meydana gelmiştir. Toplam örtüaltı sebze alanı ise aynı şekilde son beş yıl içerisinde azalmıştır.

Çizelge 6. Isparta ilinin örtüaltı sebze alanı ve üretim miktarı değişimi

Yıllar	Değişim alanı	Alçak tünel	Cam sera	Plastik sera	Yüksek tünel	Toplam
2020	Alan	-	85	4425	-	4510
	Üretim	-	584	69291	-	69875
2021	Alan	-	77	3483	-	3560
	Üretim	-	540	55951	-	56491
2022	Alan	-	77	3471	-	3548
	Üretim	-	582	56964	-	57546
2023	Alan	-	19	3311	-	3330
	Üretim	-	59	48232	-	48291
2024	Alan	-	19	3486	-	3505
	Üretim	-	59	49204	-	49263

Örtüaltı sebze üretimi de son beş yıl içerisinde azalmıştır. Isparta genelinde sera alanlarında en fazla Yorulmaz Salman ve Kevser (2014) tarafından da işaret edildiği gibi sofralık domates üretilmektedir. Bunu hıyar izlemekte, biber, marul gibi diğer sebzelerin üretimlerinde farklı dağılımlar görülmektedir.

5. SONUÇ

Batı Akdeniz Bölgesi örtüaltı sebze yetiştiriciliği ve özellikle de seracılık açısından son derece önemli bir üretim ve ihracat gücüne sahiptir. İncelenen illere göre değişmekle birlikte genel anlamda sera varlığı artmaya devam etmektedir. İlk bakışta bu artış ekonomik açıdan önemli gözükse de gelecek yıllar için dikkat edilmesi gereken hususları da taşımaktadır. Yurt içi ve yurt dışı örtüaltı sebze yetiştiriciliğinin iyi irdelenip yeni alanların kurulması buna göre planlanmalıdır. Ülkemizin stratejik öneme sahip tarla ya da meyve ürünlerinden vazgeçmesi düşünülmemelidir. Yeni sera alanları oluşturulurken yeraltı ve yerüstü su rezervleri mutlaka dikkate alınmalıdır. Yeni alanlar oluşturmak yerine eski sera alanlarının modernleşmesi sağlanmalıdır.

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THE HISTORICAL DEVELOPMENT OF AGRICULTURE: ANCIENT FOUNDATIONS TO MODERN INNOVATIONS

Bahar SANCAR[1]

1. INTRODUCTION

Agriculture is one of the most fundamental and transformative activities in human history. It is widely regarded as the basic production system that enabled the transition from a hunter-gatherer lifestyle to a settled way of life (Mazoyer & Roudart, 2006). The agricultural revolution, which began with the domestication of plants and animals, had a direct influence on food production, population growth, spatial settlement, the concept of property and forms of social organisation (Diamond, 1997). In this context, agriculture is widely regarded as the driving force behind the economic, social and cultural changes that shaped civilisations (Food and Agriculture Organization of the United Nations [FAO], 2017).

The first agricultural activities emerged in ecologically favourable regions such as Mesopotamia, the Nile Basin, the Indus Valley and the Yellow River, gradually transforming these areas into centres of agricultural knowledge and production (Smith, 1995). While primitive tools, rain-fed production and limited diversity prevailed in the early stages of agriculture, production systems became increasingly complex over time, with the development of irrigation systems and advances in soil cultivation techniques and seed selection (Blum, 2011). These

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advances ensured the permanence of settled life and paved the way for the establishment of the first urban civilisations.

Following the Industrial Revolution, the agricultural sector underwent a significant transformation, with mechanisation, chemical fertilisers and pesticides greatly increasing production efficiency (Tilman et al., 2002). The Green Revolution, which emerged in the 20th century, ensured an increase in the food supply, particularly in developing countries, through the widespread use of high-yield varieties, synthetic fertilisers, and irrigation technologies (Pingali, 2012). However, this process has caused environmental problems, including the decline of soil organic matter, water resource pollution and a decrease in biological diversity, despite short-term increases in production (Rockström et al., 2009).

Today, environmental pressures such as global climate change, drought, water scarcity and soil degradation are emerging as fundamental risks that directly threaten agricultural production (Intergovernmental Panel on Climate Change [IPCC], 2022). Furthermore, projections indicate that the global population could reach around 10 billion by 2050, highlighting the urgent need to improve the productivity and sustainability of agricultural systems (United Nations, Department of Economic and Social Affairs, Population Division [UN DESA], 2023). Against this backdrop, contemporary perceptions of agriculture are evolving through novel approaches such as precision farming, organic production, digital agricultural technologies, and agroecological methods (FAO, 2021).

This section will examine the historical development of agriculture from primitive production methods to modern digital agricultural systems. Furthermore, this section will evaluate the social, economic and environmental dimensions of agriculture together and discuss the importance of sustainable agricultural practices and future trends in agricultural transformation with a holistic approach. The aim is to position agriculture as a strategic sector that shapes the future of humanity, not just a production activity of the past.

2. AGRICULTURAL ACTIVITIES

Agriculture is the most important of the world's economic activities. The area covered by agricultural activities is also quite large and some agricultural activities. Agricultural activities use one third of the total land surface and employ a significant portion of the working population (Thoman, 1962). Only 2 percent of the working population in the United States and England are employed in agriculture, with agriculture contributing a similarly small proportion to the national income. In many developing countries, the most important contribution to the national income is provided by the agricultural sector, with more than half of the population engaged in subsistence farming. In developed countries, large agricultural lands are used and 12-30% of their income is spent on basic nutritional needs (Benites and Vaheph, 2001). Although it is stated that the problem of hunger will disappear when the food resources are considered to be equally distributed throughout the world, a significant portion of the people living in especially developing and underdeveloped countries still face the problem of nutrition. This situation also hinders developments in other sectors. because the agricultural sector not only provides food, but also provides raw materials for industrial activities (TUIK, 2020). Despite its decreasing share in the economy, the agricultural sector is in a strategic position in terms of rural development and food security. Solving the problems of hunger and malnutrition in developing and underdeveloped countries is possible by meeting the demands for balanced and healthier nutrition in developed countries, giving the necessary importance to agricultural activities and increasing the importance given. At the same time, since agriculture is based on the use of water, energy and land, it is foreseen that the improvements to be made in the sector will also contribute to the protection of nature and natural resources (Artmann and Sartison, 2018; Dadashpoor and Malekzadeh, 2020).

For years, agriculture has been associated with the production of vital food products. Agricultural activities are only applied to agricultural products with biological standard presence until harvest time. In this context, it is not applied to post-harvest agricultural products (Seto et al. 2011). For example, wheat production is an agricultural activity, but flour production from wheat is not an agricultural activity because it is post-harvest production. The area covered by agricultural activities is quite large. Agricultural activities include a wide range of activities such as animal husbandry, forestry, annual or longer-term aquaculture, fruit garden, floriculture, aquaculture, etc.

The importance of agricultural activities for the country's economy is evident from the following (Seto et al., 2011; d'Amour et al., 2017; Solecka et al., 2017):

Livelihood: Many people depend on agriculture for their livelihood; approximately 70% of the population earns their living directly from agriculture. This high proportion in the agricultural sector is the result of non-agricultural activities failing to absorb the rapidly growing population. However, populations in developed countries are not primarily based on agriculture.

Contribution to national income: Most developing countries rely heavily on agriculture for their national income. By contrast, agriculture contributes the least to the national income of developed countries.

Feed and feed supply: Feed and silage are produced for pets. In addition, livestock provides milk and protein for human consumption.

Importance for international trade: Various agricultural commodities, such as sugar, tea, rice, cotton, tobacco and coffee, are mainly exported to other countries. This practice helps countries reduce their current account deficit and save foreign currency. This can then be used to import vital machinery, raw materials, and infrastructure to support the country's economic development.

Marketable Share: Having an additional marketable share is an indicator of the development of the agricultural sector. Most of the population can meet the surplus of the country's marketable share due to food production related to manufacturing and mining. As the agricultural sector develops, production increases and this leads to the expansion of the surplus of marketable share. Thus, surpluses can be exported to other countries.

Farm Mechanization: It enriches the economy with the introduction of farm mechanization, which plays an active role in the agricultural sector. The use of modern machinery in agricultural lands leads to maximum efficiency and quality product production. Thus, the supply of raw materials to industries increases.

Role of Livestock: Livestock provides the highest contribution to economic growth. Annual protein per capita corresponds to 18 kg of meat and 155 liters of milk. Dairy and meat products have reasonable market value. Farmers earn a good livelihood by producing these products and putting them on the market.

3. HISTORY OF AGRICULTURE

Agriculture, or farming, is the science of producing, improving the quality and efficiency of, storing in the right conditions, processing, evaluating and marketing plant and animal products. In other words, it encompasses all activities related to the maintenance, feeding, breeding, protection and mechanisation of agricultural animals and their products, which can be used as human food and have economic value. It also encompasses all fishing activities in stagnant waters or designated areas (Bar-Yosef, 1998). Agriculture comprises two major production sectors: Crop production and animal production. The only difference between these branches, and indeed their definitions, is the material used. Agriculture is an applied science that aims to generate economic value for people's benefit (Bellwood, 1997).

The history of agriculture dates back 10,000 years. Following its initial development, agriculture spread worldwide as a result of interaction between societies. Thanks to agriculture, humanity was able to settle down, which led to the formation of today's states. Although methods such as fertilisation and planting are ancient, their use has increased significantly over the last century (Lev-Yadun et al., 2000).

3.1. Agriculture in ancient times

In ancient times, agriculture — the earliest examples of which were found in the Fertile Crescent and the surrounding region — transformed societies that had previously relied on gathering and hunting into settled communities (Binford, 1968). In the same period, agriculture began to be practised using different methods in China and other Asian countries, and over time it became more intensive in and around the Nile River. The oldest agricultural data in history come from the Anatolian settlement of Abu Hurerya. These date from 13,500 years ago.

Traces of agricultural activities have also been found in the Levant and around the Zagros Mountains in Iran. Simultaneously, remains of crops such as millet, barley, grain, lupine, flax and wheat have been discovered in regions above the Fertile Crescent (Ammerman & Cavalli-Sforza, 1984; Cohen & Armelagos, 1984; Marshall, 2000).

Most theories suggest that the first agriculture began when people started leaving plant foods and seeds they had gathered from the wild outside their caves. They realised that, rather than searching for food all day, they could have a continuous supply by planting the seeds. Different societies made this discovery at different times. The agricultural activities, which first emerged in Anatolia and the Middle East, have spread around the world through social interactions. Those societies who discovered agriculture earlier had already settled and the bases of the modern-day civilizations were formed (Smith, 1995; Smith, 2002).

Agriculture originated in India around 7000 BC and later spread to other parts of Asia some 2000 years afterwards. By that time, the agricultural structures had appeared along the Nile River. The high flow of water and comfortable temperature gave a better output to agriculture in Egypt. The Egyptians knew how to reckon the flooding time of the Nile, and they performed specific mathematical formulas and geometrical calculations to save their crops (Rindos, 1984; Renfrew, 1987).

Originally, agricultural activities took place in Mesopotamia and were developed by the Sumerians along the Shatt al-Arab and the Persian Gulf. It is believed that this process started about 5000 BC, later spreading to other Mesopotamian civilizations with time. Studies have shown barn animal bones within the Euphrates and the Tigris. This evidence means that animal husbandry was also carried out in the area. Around the same time as these early practices, indigenous peoples began agricultural activities in the Americas, especially in the Andes Mountains. The activities here were mainly characterized by stepped terracing of the mountain. Excavation projects along the Pacific coast of South America revealed remains of agricultural produce such as tobacco, potatoes, beans, peppers, tomatoes, and pumpkins. Bothmer et al., 1995; Harris & Gosden, 1996).

Agricultural activities were also important in ancient Greece and Rome. While the Greeks cultivated Mediterranean crops such as olives, cotton and corn, the scarcity of their land prevented them from making significant progress in this area. In contrast, the Romans traded grain products (Bothmer et al., 1985; Badr et al., 2000).

3.2. Agriculture in the middle ages

The fact that the Islamic world was at a highly advanced level of civilisation during the Middle Ages reveals tremendous progress in agricultural activities and animal husbandry in and outside the Middle East during this period. The Arabs produced pumps which employed hydraulic and hydrostatic techniques for advancing levels of production. Using water mills, Muslim farmers could easily transport water, hence keeping drought away from their irrigation systems. In this age, a wide range of agricultural produce was grown, including cotton, citrus fruits, apricots, saffron, artichokes and sugar beets. This range of temperate agricultural produce was carried on to Europe by way of the Arab and Umayyad states of Spain, which exported lemons, almonds, figs, oranges, cotton, and bananas across the continent. Meanwhile, the use of the plough was an important innovation to Asian agriculture in China during the millennium dating from (Banning 1998; Barkai & Liran 2008).

With the end of Roman domination in Western Europe following the Migration of Tribes, the population rapidly increased in these areas. In order to feed them, more land had to be brought under cultivation. Forests and swamps were, therefore, converted into arable land. For ploughing such extensive areas, heavy ploughs pulled by oxen were used. Over time clayey soils, difficult to work, came to be tilled using 8–10 oxen (Rollefson et al., 1992; Barkai, 2011). At that time, the Romans practised crop rotation, growing grain one year and leaving the land fallow the next. Over time, the peoples of Europe learned to sow oats, rye and barley. Thus, while the land was cultivated in the winter and spring of one year, it was left fallow the following year (Bocquet-Appel and Bar-Yosef, 2008; Bocquet-Appel, 2011).

The open field system was implemented in Europe in the 800s. According to this system, every farmer grew a variety of agricultural products on land with long, narrow fields. Such fields were often constructed on sloping ground so that excess water could be drained down deep ditches. Under the open field system, each farmer grew their own field to support their family. However, fertilising and ploughing were done using division of labor. This system remained in use in Europe until the start of the 20^(th) century. During the Middle Ages, nearly all agricultural operations were performed using hand tools. While this reduced yields considerably, some produce was also lost due to late harvesting (Valla et al., 2002; Weninger et al., 2009).

Many people died in Europe as a result of the plague epidemics in the 14th century. The population further decreased rapidly due to the Hundred Years' War, which broke out during the same time. Due to these events, agriculture faced a decline and people were unable to feed themselves properly. Later on, fields, particularly in England, were enclosed, and commercial cultivation was started in these enclosed fields. As a result of this, for the first time, agricultural markets were established in cities in Europe. Therefore, people living in cities were provided with easy access to the agricultural products, which was very handy.

Thus, the urban populations increased significantly (Kuijt and Goring-Morris, 2002; Hill, 2009).

3.3. Modernization in agriculture

Throughout history, large-scale agricultural production has always presented significant challenges. The first of these is providing nutrients for crops. Traditionally, people have used animal excrement as fertiliser, left their land fallow and rotated their crops (Bocquet-Appel, 2011; Rosen & Rivera-Collazo, 2012).

A great revolution occurred in the Western world in the 18th century, particularly in England. The introduction of turnip and clover cultivation meant that land no longer needed to be left fallow. Turnips play an important role in animal production as a winter food source, and thanks to them, both the number of animals produced and those fed has increased. Consequently, as the number of animals increased, so did the amount of manure produced (Hill, 2009; Liran & Barkai, 2011).

Another significant development was the quadruple rotation system devised by the English farmers Viscount Charles Townshend and Thomas William Coke, who were both from Norfolk. This method involved planting wheat, turnips, barley and clover consecutively in fields, thus eliminating the need for fallow land. During this period, quality animals were also selected from other species. Townshend and Coke thus obtained fertile species and added clay and chalk to the poor, sandy Norfolk soil to increase the yield. In contrast, the adoption of new methods was slower in Europe, where French and German farmers were reluctant to abandon traditional cultivation techniques (Ucko and Dimbleby, 1969; Rosen and Rivera-Collazo, 2012). As the industry developed, many other innovations followed. Cast iron was first used in ploughs, rollers and harrows. In 1840, the German chemist Justus von Liebig discovered that plants needed potassium, phosphorus and nitrogen to develop properly. The importance of different types of soil and fertilisers in increasing agricultural yields was also recognised. Meanwhile, in England, John Lawes and Henry Gilbert produced artificial fertiliser by reacting phosphate-rich rocks with sulphuric acid. This marked the beginning of the use of artificial fertilisers as we know them today. In 1843, clay drainage pipes were invented, and large fields were subsequently fitted with inexpensive, straightforward drainage systems. These developments opened a new era in agriculture, demonstrating that agricultural activities worldwide generate economic income through market sales (Boyle and Ardill, 1989; Delate and Combardella, 2000; Kim et al., 2009).

The situation in some European countries, however, has been different. In France, for example, when the nobles started living around the palace instead of on their own estates, the land was gradually taken over by the peasants. By 1789, 40% of France's land was owned by peasants. Such agricultural developments have also radically altered social life, with similar changes occurring across the globe, particularly in rural European areas (Weninger et al., 2009; Willcox et al., 2009).

3.4. Agriculture today

Today, agriculture is primarily carried out for commercial purposes. Advances in transportation mean that agricultural products can now be transported cheaply and quickly, even to distant settlements. Before the end of the 19th century, Europe imported grain, dairy products and salted meat from America. As storage and cooling methods improved, Europe began to engage in agricultural trade with many countries. During the First World War, when transportation became difficult, farmers around the world sold their produce to Europe at high prices. After this period, Europe entered into great competition with America (Altieri and Anderson, 1992; Altieri and Rosset, 1996).

When European countries were unable to make sufficient progress in agriculture, some, especially England, turned to animal husbandry and started producing milk and dairy products. Scientists in this area have achieved efficient production by crossing their fattened pets. Denmark and the Netherlands in particular have advanced Europe in this field by selling dairy products to other countries. However, World War II dealt another blow to this progress, causing production in Europe to decline drastically. Consequently, many European countries faced the threat of famine for a long time (Gebbers & Adamchuk, 2010; Grassi, 2014).

Thanks to scientific developments, agricultural activities can now be carried out in a wide range of geographical areas and conditions. Changes made to the genes of plants and animals mean that the risks of certain species contracting diseases can be reduced. However, although agricultural spraying increases yield, it also harms nature and crop quality. Furthermore, animals are given hormones to produce more meat and milk in a shorter time. This method is also used in crop production to ensure that herbal products are produced more abundantly. However, in meat and milk production, overfeeding animals in small enclosures and preventing them from seeing daylight creates a productivity-enhancing effect. This also reduces product quality and authenticity. Advanced vaccination techniques combat the disease risks faced by animal and plant species. Additionally, the shift towards organic agriculture, particularly in Western societies, is gaining attention (McBratney et al., 2005; Lichtfouse et al., 2009).

3.5. View of agriculture by country

Agriculture played a significant role in humanity's transition to collective living. Although it remained the main source of livelihood for most people until the Industrial

Revolution, significant developments in agriculture and technology have occurred in recent years. Significant changes to agriculture occurred, particularly during the 20th century (Richards et al., 2018; Rüegg et al., 2018). Conversely, many governments worldwide invest in agriculture to ensure the production of quality food. Much of this investment is directed towards wheat, corn, rice, soybeans and milk. However, many investments in developed countries are ineffective and harmful to the environment.

The mechanisation of agriculture, accompanied by the use of artificial fertilisers, causes significant environmental damage, particularly in terms of water pollution. In the 21st century, as environmental problems and abnormal natural events have emerged, especially global warming, the level of mechanisation with the addition of artificial fertilisers applied to agriculture has begun to be reduced (Piñeiro and Viglizzo, 2018; Piñeiro et al., 2020).

First discussed at the turn of the 20th century as an alternative to the environmental damage occurring from conventional farming techniques, organic agriculture provides a solution to these problems. While the practice garners significant worldwide attention, organic farming due to its expense is only affordable to the upper classes of the population. The largest supporter of this type of agriculture in the world is the European Union. The EU named the practice 'organic agriculture' when adding it to their literature in 1991, and the practice took off with the formation of the CAP organisation in 2005. One of the most prevailing problems addressed by organic farming is food filled with hormones created by the farming process (McIntyre et al., 2009).

Consequently, at the end of the year 2007, many agricultural commodities, especially grain, have seen price increases in the fluctuating global economy. In the future, food wars are foreseen to break out in Africa and many other developing countries due to increasing food prices. The United Nations predicts that by 2025, Africa will only feed 25% of its population.

Agriculture nowadays has two different goals. The first group comprises those people who grow food only to feed their families. The second group comprises the individuals and organisations that are involved in the commercial part of agriculture. For industrial agriculture, the focus is on trade, so there is immense potential for fertilisation, seeding, its maintenance, and irrigation. Similarly, the areas that it covers are large. Development in agricultural chemistry in particular helped increase production with less need for labor in the 20th century. However these have resulted in not only the production of unhealthy food, but also unemployment.

Although pesticides used in agriculture prevent damage to a great extent caused by pests, they disturb the natural balance and result in harming the environment. Despite that, agricultural machinery like tractors increases the production and feeds more people. A sharp rise in agricultural production was seen in the 20th century, which replaced the primitive tools of agriculture with modern machinery and irrigation system. Mechanisation in agriculture is ranked as one of the 20 greatest revolutions in the world according to the United States' National Academy of Engineering. According to data in 1999, modern technology has enabled a single farmer to feed more than 130 people (Witkowski and Medina, 2016; Witkowski et al., 2016). The major issues that are affecting agricultural production and economy includes environmental impact, pesticides, climate change, and relation of agriculture with oil.

4. RESULT

Throughout the process stretching from the dawn of human history to the present day, agriculture has evolved beyond being merely a production activity, becoming one of the fundamental dynamics that shape societies' economic structures, social organisation and relationship with the environment. Agriculture played a pivotal role in the transition from a hunter-gatherer lifestyle to a settled life, making the emergence and development of civilisations possible. With the creation of surplus production came the foundations for phenomena such as trade, specialisation, and urbanisation. Thus, when considered within the context of historical continuity, agriculture has played an indispensable role in the development of human civilisation.

Technological developments, particularly modern production techniques developed in the 20th century, have increased agricultural production and contributed to a significant increase in the global food supply. However, the intensive, input-based production models adopted during this process have led to increased pressure on natural resources and disrupted ecosystem balance. Declining soil fertility, water pollution, loss of biodiversity and negative climate change effects on agricultural production make it imperative for the agricultural sector to re-examine its current production approach.

Today, agriculture not only faces the responsibility of feeding a growing world population, but also the multidimensional task of ensuring environmental sustainability, adapting to climate change and protecting natural resources. In this context, unlike traditional production models, sustainable agriculture approaches present a concept that considers ecological integrity, prioritises efficient resource use and aims to minimise environmental impact. Examples of such approaches include precision agriculture practices, digital technologies, agroecological methods, and climate-friendly production. Precision agriculture practices, digital technologies, agroecological methods and climate-friendly production systems will be key to the future of agriculture.

Consequently, agriculture will remain of strategic importance to humanity's survival, as it has been in the past. However, ensuring this continuity will require a shift in focus from production to a new agricultural paradigm that considers environmental, social, and economic factors holistically. Therefore, sustainability should be considered a prerequisite for shaping agricultural policies, scientific research and educational activities, in order to leave future generations with a liveable environment and a secure food system. Experience gained from the historical development of agriculture should inform the design of future agricultural systems, with long-term strategies that consider not only today's needs, but also those of tomorrow.

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SEED COATING SYSTEMS IN MODERN SEED TECHNOLOGIES

Elif ÇATIKKAŞ[1]

1. INTRODUCTION

Seed coating has become a key strategy in modern and sustainable agriculture. This technology aims to optimize plant development from germination by overcoming performance limitations caused by environmental stresses, storage conditions, and genetic factors (Javed et al., 2022). Thin coatings applied to the seed surface allow for the direct and controlled delivery of nutrients, microbial inoculants, biostimulants, and protective agents (Javed et al., 2022; Kavusi et al., 2023). Such applications enhance germination rate and speed, produce stronger and more vigorous seedlings, and contribute to uniform field establishment, ultimately improving crop yield (Panda & Mondal, 2020). In addition, these coatings increase seedling resilience against biotic and abiotic stresses, reduce the need for chemical inputs, and promote efficient resource use and sustainability (Javed et al., 2022; Panda & Mondal, 2020). Accordingly, seed coating is regarded as a scalable solution to global challenges such as climate change, soil degradation, and food security (Rahman et al., 2024).

Considering the critical role of high-quality seeds in achieving increased yields (with reports indicating up to 30% yield improvements from using high-quality seeds (Afzal ve ark., 2016), post-sowing performance is equally important. Seeds are

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exposed to various stress factors during germination and emergence that can significantly affect their performance (Zinsmeister ve ark., 2020). Appropriately selected and applied chemical, biochemical, and biological seed treatments play a crucial role in improving emergence success, early seedling development, and ultimate yield potential (Sharma ve ark., 2020). These applications, widely adopted by both the commercial seed industry and producers, have become indispensable tools for protecting plant health and supporting seedling growth (Afzal ve ark.,2020; Taylor ve ark., 2020). In the context of sustainable agriculture, there is growing interest in approved biological treatments, especially for organic farming. This trend further emphasizes the importance of innovative seed coating technologies that allow for effective and controlled delivery of active components to seeds (Taylor ve ark., 1990, Pedrini ve ark., 2020).

The economic significance of seed coating technologies is also increasing. The global market for seed coating materials was approximately USD 1.8 billion in 2019 and is expected to reach USD 3.0 billion by 2025 Markets and Markets (2020). While chemical treatments still hold the largest market share (USD 3–5 billion in 2020) (Taylor ve ark., 2020), demand for biological seed treatments, including biofertilizers, biopesticides, and biostimulants, is rapidly growing (USD 1–1.5 billion in 2020) (Taylor ve ark., 2020; Biological Products Industry Alliance, 2018). Thus, seed coating technologies not only provide agronomic benefits but also represent a rapidly expanding economic sector that supports the transition to sustainable agriculture.

2. COMPONENTS USED IN SEED COATING AND THEIR FUNCTIONS

Active components used in seed coating aim to improve seed and seedling performance by promoting germination, early seedling development, and subsequent plant growth. Depending on their mode of action, these components may exhibit protective and/or growth-enhancing properties (Taylor et al., 2020). In contemporary seed coating practices, biostimulants, plant nutrients, agents providing protection against biotic and abiotic stresses, and biological inoculants are widely utilized. In particular, seed protectants containing fungicides, insecticides, nematicides, and bactericides play a crucial role in controlling pathogens and pests at sowing (Rocha et al., 2019). In addition, selected bacteria and fungi are considered biological inputs for plant protection and nitrogen fixation purposes (Rocha et al., 2019; Ma et al., 2019).

To mitigate the adverse effects of abiotic stresses such as salinity and drought that may occur after sowing, both biological- and synthetic-based seed treatments are employed. In this context, studies investigating the use of elicitors as active components for pest management (Kalaivani et al., 2016; Lee et al., 2016) and for enhancing drought stress tolerance (Tayyab et al., 2020) have increased. In recent years, interest in and demand for biostimulant and nutrient based seed applications have grown markedly (Pedrini et al., 2017).

The persistence of active ingredients on the seed surface from storage until sowing is critical to the success of the application. Therefore, binders and adjuvants are incorporated into coating formulations. Colorants facilitate the easy identification of coated seeds and contribute to the visual assessment of application uniformity (Pedrini et al., 2017). In liquid formulations, water serves as the primary carrier, and lowviscosity solutions are preferred to ensure effective atomization. Since most active ingredients have limited solubility in water, surfactants are commonly used in the preparation of aqueous formulations (Buffington et al., 2018). Moreover, certain surfactants have been reported to directly enhance germination and seedling emergence (Madsen et al., 2017).

Binders used in coating processes ensure the adhesion of applied materials to the seed surface, maintaining coating integrity after drying and preventing dusting and cracking during handling and sowing (Afzal et al., 2006). Both organic- and synthetic-based polymers are widely used for this purpose (Ryu et al., 2006; Danielson et al., 2011). Solid particles, on the other hand, function as filler materials that form the physical layer of the coating; they must be selected to provide a uniform surface without impeding radicle emergence (Taylor et al., 2003). These materials are generally low cost, non-toxic, and applicable in fine powder form (Kangsopa et al., 2018).

3. TYPES OF SEED COATING

3.1. Dry Powder Coating

Dry powder coating is a method based on mixing seeds with dry powders and is traditionally known as the “planter box application” (Taylor, 2003). Dry powders may consist of dried microbial formulations or other coating materials applied to seeds, and following application, seed shelf life may be temporarily reduced (Taylor, 2003). The equipment used in this method distributes the powder evenly and precisely onto the seed surface through rotating brushes, screw, or conveyor systems, and the machinery is calibrated according to seed weight (Figure 1). Dry powders can reduce friction between seeds, thereby improving flowability and singulation during sowing. The most commonly used dry powders are talc and graphite (Anderson et al., 2014). Recent studies indicate that soy-based protein can be used as an environmentally friendly and effective seed lubricant and may reduce dust formation during sowing (Badua et al., 2019). The dose of dry powder applied to seeds is limited by its adhesion capacity to the seed surface and typically ranges from 0.06 to 1.0% of seed weight (Figure 2). In small-seeded species, the increased surface area results in a higher powder retention capacity (Anderson et al., 2014).

3.2. Dry Powder Coating

When low amounts of active ingredients are required, seed dressing is the most widely used application method (Kimmelshue et al., 2019). Although various types of equipment are available for seed coating (Jeffs, 1986), the rotating coating machine is the most commonly used system in practice (Figure 1). In this method, liquid formulations are delivered onto a rotating disc, atomized into fine droplets, and uniformly distributed onto seeds moving within a metal cylinder; once coating is completed, the seeds are discharged from the system. A wide range of active ingredients, particularly chemical crop protection products, can be effectively applied using this technique.

The application rates of liquid formulations to seeds generally range from levels below 0.05% up to 1% of seed weight (Figure 2). In chemical seed treatments, especially when higher doses of insecticides are required, flowability or finishing powders are added immediately after liquid application to bind excess liquid (Anderson, 2014). These dry powders can be applied either directly into the rotary coating device during the process or after treatment using dry coating equipment (Figure 1).

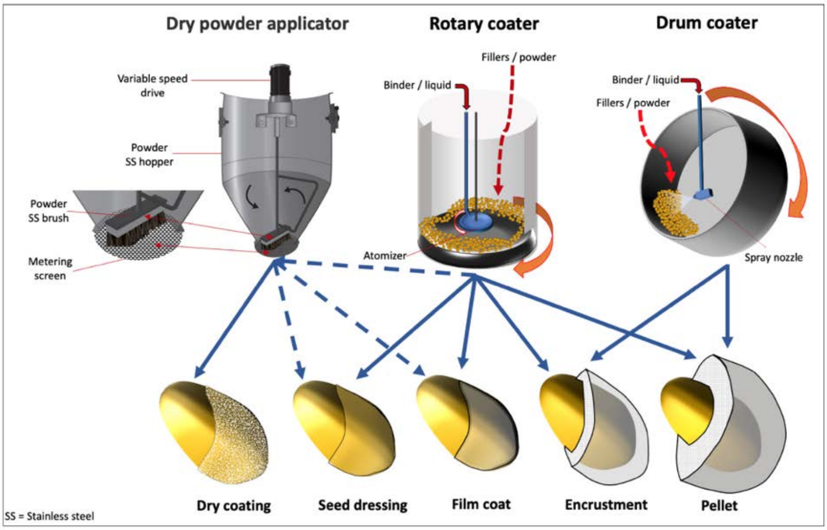

Figure 1. The three main types of equipment used in seed coating Technologies dry powder applicators, rotary coaters, and drum coaters enable the application of five different coating types: dry coating, seed dressing, film coating, encrusting, and pelleting (Afzal et al., 2020).

3.3. Film Coating

The film coating technique, originally developed in the pharmaceutical and confectionery industries, was later adapted for seed coating applications (Taylor, 2003). In this method, a thin, continuous film layer is applied to the seed surface, most commonly using rotary coating machines (Figure 1). Polymer-based liquid coating materials are formulated to dissolve and uniformly distribute active ingredients. Film coating has been reported to achieve approximately 90% application efficiency while causing minimal changes in seed shape and size (Taylor and Harman, 1990; Pedrini et al., 2017). Owing to improvements in germination performance and reduced dust-off, film coating has become one of the most widely used methods in seed technologies (Taylor, 2003).

In film coating, seed weight typically increases by 2–5% (Taylor, 2020). For higher loadings, equipment with enhanced drying capacity, such as aerated pans or fluidized bed systems, is required (Black and Bewley, 2000). In addition, dry finishing powders may be added to the rotary coater to increase the coating load to approximately 5–8% (Figure 2).

The selection of film-forming polymers is of critical importance for both sowing performance and environmental safety (Halmer, 2006; Hill, 1999). For example, maize seeds coated with PolySeed CF have been reported to produce less dust and reduce insecticide loss compared with uncoated seeds (Avelar et al., 2012).

3.4. Encrusting

Encrusting is a coating method achieved by the controlled addition of liquid and solid particles onto the seed surface. This process ensures complete seed coverage while largely preserving the natural seed form (Taylor et al., 2020). In the literature, encrusted seeds are sometimes referred to as “mini-pellets” or simply as “coated seeds” (Taylor, 2003). The most commonly used equipment for producing this type of coating includes rotary coaters and coating pans (Figure 1). Because large amounts of water are used during application, seeds must be dried after treatment to return them to their initial moisture content before packaging. As a result of encrusting, seed weight may increase over a wide range, from 8% up to 500% (Figure 2).

Research has shown that encrusting can improve seedling emergence performance. For instance, in fescue seeds, encrusting applied prior to storage resulted in significantly higher germination compared with post-storage treatments and untreated seeds (Olivera et al., 2007). However, because coating thickness and seed weight gain can influence germination rate, encrusted seeds may germinate more slowly than film-coated seeds (Gorim and Asch, 2012). Moreover, the amount of binder plays a key role in determining mechanical properties such as coating durability, resistance to abrasion and compaction, and water solubility or disintegration time (Qiu et al., 2020).

3.5. Pelleting

Pelleting is an advanced form of encrusting in which the original shape of the seed is completely lost due to the increased coating load (Pedrini et al., 2017; Taylor, 2020). In this process, various mineral filler materials and binders are used; binders may be applied in liquid or dry powder form and are mixed with filler materials to create the coating matrix. Following pelleting, a substantial increase in seed weight typically occurs, ranging from 500% to 5000%. This increase is commonly expressed as the ratio of seed weight to the weight of the pelleted product (Figure 2).

The appropriate selection and compatibility of filler materials and liquid components are crucial to avoid inhibition of germination within the pellet matrix (Taylor, 2020). Pelleted seeds are particularly preferred for small seeded, high value vegetable crops where precision sowing is required. Common examples include lettuce, onion, carrot, and tobacco (Taylor, 2003; Kangsopa et al., 2018; Javed and Afzal, 2018; Sikhao et al., 2020). The physical properties of materials used in pelleting such as particle size distribution, porosity, water-holding capacity, and non-toxicity directly influence coating performance (Kangsopa et al., 2018). For instance, combinations of bentonite with talc or pumice have produced successful results in tobacco seeds, whereas diatomaceous earth for broccoli and mixtures of calcium carbonate and gypsum have been found effective for lettuce (Guan et al., 2013; Amirkhani et al., 2016).

In certain specific cases, components such as calcium peroxide are added to the pellet mixture to enhance germination under oxygen-limited conditions; this approach has been shown to increase emergence rates in submerged rice cultivation (Mei et al., 2017). Because pelleting requires comprehensive and controlled application of active ingredients, liquids, and solid particles, it demands greater expertise and time compared with other coating techniques. In addition, coating integrity is closely related to the type of materials used and the application technology employed (Taylor and Harman, 1990).

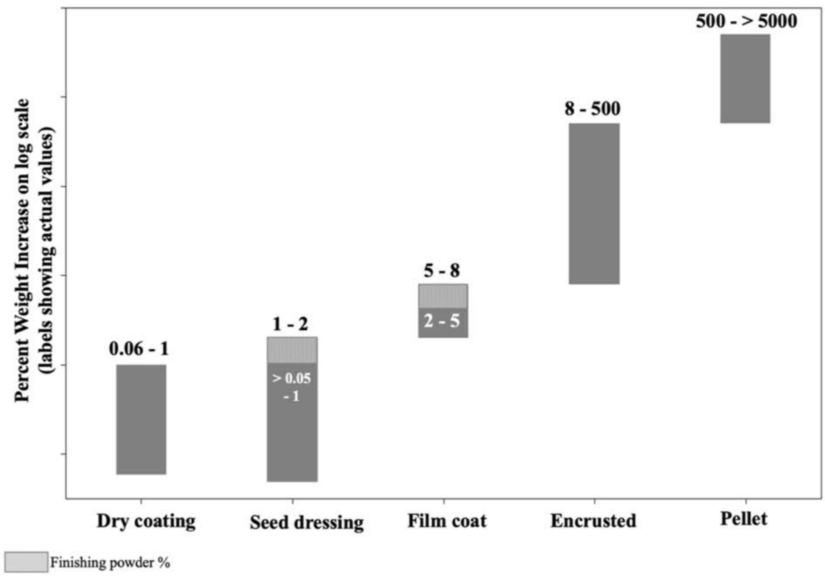

Figure 2. Percentage weight increase observed after different seed coating technologies. The grey area represents the finishing powder added during application in seed dressing and film coating. For comparison purposes, the values are presented on a logarithmic scale (Afzal et al., 2020).

3.6. Biological Seed Coating

Various seed coating materials have been developed to enhance seed performance and support early plant growth. Biochar, a carbon-rich material produced through the pyrolysis of biomass, is applied in seed coatings due to its high water-holding capacity and its ability to stimulate microbial activity. In addition, biochar improves soil properties and contributes to increased carbon sequestration (Tauqeer et al., 2022).

3.6.1. Biochar Based Seed Coating

Biochar is a material obtained by converting organic matter into a carbon-rich form via pyrolysis. Owing to its high water retention capacity and its ability to support microbial activity, it is preferred in seed coating applications. Studies have shown that biochar improves soil structure and enhances carbon accumulation (Tauqeer et al., 2022).

3.6.2. Alginate Based Seed Coating

Alginate is a natural polymer widely used in the preparation of hydrogels with controlled or delayed release properties. Derived from brown algae, this material is easy to produce, environmentally friendly, biodegradable, and non-toxic. In agriculture, alginate is commonly used as a slow-release coating material or as a carrier for fertilizer elements (Skrzypczak et al., 2021).

3.6.3. Chitosan Based Seed Coating

Chitosan is a biodegradable polymer derived from chitin. It promotes germination by enhancing water uptake, nutrient utilization, and tolerance to stress conditions. In addition, it stimulates overall plant development, positively affecting yield, chlorophyll content, and root and shoot growth. Chitosan coatings offer an environmentally friendly and sustainable alternative to synthetic chemicals in agriculture (Riseh et al., 2024).

3.7. Biological Seed Coating

Plant-beneficial microorganisms (PBM) play a crucial role in sustainable agricultural practices due to their ability to enhance nutrient uptake, increase tolerance to environmental stresses, and provide resistance against pathogens. This group includes plant growth promoting bacteria (PGPB), mycorrhizal fungi, and rhizobia. Through plant microorganism interactions, PBMs contribute to processes such as stimulation of root development, nitrogen fixation, phytohormone production, and improved water and nutrient uptake (Paravar et al., 2023).

Microbial seed coatings represent an innovative approach aimed at harnessing these beneficial effects of PBMs during the early stages of plant development. In particular, PGPB belonging to the genera *Pseudomonas* and *Bacillus* are widely used due to their potential to enhance plant vigor and suppress pathogen infections. *Rhizobium* species, which are notable for their nitrogen-fixing capacity, are also frequently incorporated into seed coating formulations, often in combination with other beneficial microorganisms (Rocha et al., 2019). However, it has been reported that certain coating components (e.g., lime or fungicides) may reduce the effectiveness of *Rhizobium* (Adams and Lowther, 1970).

Among fungal PBMs, *Trichoderma* species have shown significant success in promoting germination, supporting plant growth, and providing biocontrol against soil-borne pathogens such as *Rhizoctonia solani* and *Fusarium* spp. The combined application of *Trichoderma* with arbuscular mycorrhizal (AM) fungi has been reported to enhance growth performance in some field crops, such as wheat (Anjaiah et al., 2006). In addition, *Aspergillus* and *Gliocladium* species have also been investigated for their biological control potential (Adholeya et al., 2005).

Although the combined use of multiple PBMs can enhance plant resilience, in some cases single inoculations have been found to be more effective. For example, the co-application of *Trichoderma* with other microorganisms was reported to suppress germination in lettuce, whereas its sole application resulted in more favorable outcomes. Similarly, while certain co-inoculation formulations did not enhance growth in cowpea, treatments containing only *Pseudomonas* led to improved plant development (Abdela et al., 2020). A seed coating agent designed to enhance microorganism-induced tolerance in barley is shown in Figure 3.

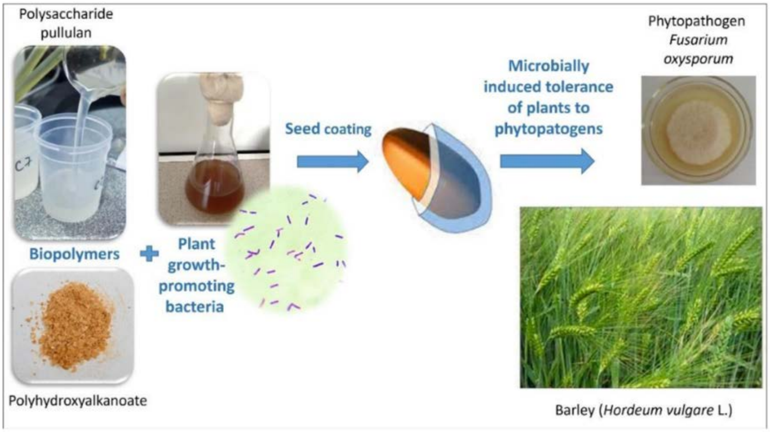

Figure 3. Microbial-based seed coating agents aimed at enhancing stress tolerance in barley (Usmanova et al., 2024).

Environmentally friendly seed coatings, such as chitosan and other biodegradable materials, offer a range of advantages for sustainable agriculture. These coatings promote root development by enhancing water and nutrient uptake, improve seed germination and overall plant growth, and ultimately increase yield and plant resilience (Riseh et al., 2024). In addition to stimulating growth, some eco-friendly coating formulations have demonstrated more than 80% effectiveness in controlling diseases and pests, while natural extracts support seedling health through their insecticidal and antibacterial properties (Fang et al., 2023; Wei et al., 2019). Moreover, being produced from non-toxic and environmentally benign biological materials, these coatings help reduce pollution and pesticide residues, thereby protecting both human health and ecosystems and supporting sustainable agricultural practices (Wei et al., 2019).

4. BENEFITS OF ENVIRONMENTALLY FRIENDLY SEED COATING TECHNIQUES

Environmentally friendly seed coatings, such as chitosan and other biodegradable materials, offer a range of advantages for sustainable agriculture. These coatings promote root development by enhancing water and nutrient uptake, improve seed germination and overall plant growth, and ultimately increase yield and plant resilience (Riseh et al., 2024). In addition to stimulating growth, some eco-friendly coating formulations have demonstrated more than 80% effectiveness in controlling diseases and pests, while natural extracts support seedling health through their insecticidal and antibacterial properties (Fang et al., 2023; Wei et al., 2019). Moreover, being produced from non-toxic and environmentally benign biological materials, these coatings help reduce pollution and pesticide residues, thereby protecting both human health and ecosystems and supporting sustainable agricultural practices (Wei et al., 2019).

In conclusion, seed coating technologies stand out as effective tools for enhancing germination, early seedling development, and stress tolerance by enabling the controlled and targeted delivery of active ingredients. Alongside conventional approaches, the development of biological and environmentally friendly coating materials contributes to increased agricultural productivity and the promotion of sustainable production systems. In the future, the wider adoption of coating formulations optimized for specific species and environmental conditions is expected to further strengthen the strategic importance of modern seed technologies in agriculture.

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DERİM SONRASI OZON UYGULAMALARININ BAHÇE ÜRÜNLERİNDE ANTİOKSİDAN SAVUNMA SİSTEMLERİ ÜZERİNE ETKİSİ

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1. DERİM SONRASI DÖNEMDE OZON UYGULAMALARI

Bahçe ürünlerinin derim sonrası metabolik aktiviteleri, kaliteleri ve pazarlama süreci, ürünlerin olgunlaşıncaya kadar geçen dönemde uygulanan faktörlere (derim, derim zamanı, derim olgunluğu, derim öncesi kültürel işlemler, beslenme vb.) bağlıdır. Kısaca, bir ürünün bahçeden sofraya kadar olan süreçte, kaliteli olarak kalmasında olgunlaşma dönemindeyken yapılan uygulamalar önemlidir. Bu nedenle bahçe ürünlerinde derim sonrası yapılan tüm uygulamalar, mevcut kaliteyi korumak ve ürünlerin bulundukları koşullarda savunma sistemlerinin güçlenmesi sağlamak adına yapılmaktadır (Türk vd., 2017). Bahçe ürünlerinde olgunlaşma ve yaşlanmayla birlikte fiziksel, kimyasal ve biyokimyasal değişimler ve kayıplar meydana gelmektedir. Bu değişiklikler ve kayıplar derim sonrası birçok faktörden (sıcaklık, nem, depolama koşulu vb.) etkilense de zaman zaman ciddi boyutlara ulaşmaktadır. Derim sonrası

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dönemde görülen kayıpların ana sebepleri arasında mikrobiyolojik bozulmalar ve çürümelerin önemli yer tuttuğu bilinmektedir (Şimşek ve Koyuncu, 2024). Özellikle küf kaynaklı bozulmalar nedeniyle oluşan mikotoksinler, insan sağlığını olumsuz yönde etkilemektedir (Saygılı vd., 2025). Bu süreçte ürünlerin kalitesinin korunmasında soğukta muhafazaya ek olarak farklı uygulamalar yapılmaktadır. Bunlar arasında yer alan en yaygın yöntem fungusit uygulamasıdır. Ancak tarımsal üretimde kullanılan fungusitler kalıntı sorunu sebebiyle insan sağlığı üzerine olumsuz etkilere neden olabilmektedir (Arslantürk vd., 2025). Ayrıca pestisitlerin artan dozlarda ve kontrolsüz kullanımının patojenlerin bu maddelere karşı dayanım kazanmasına sebep olmaktadır (García-Martín vd., 2018). Kimyasal yöntemlere karşı çevre dostu olan alternatif yöntemler düşünüldüğünde, uzun yıllardır birçok alanda dezenfekte edici özelliği ile öne çıkan ozon (O_3) uygulamaları dikkat çekmektedir (Sitoe vd., 2025). Ozon ilk kez 19. yüzyılın ortalarında Alman kimyager Christian Friedrich Schönbein tarafından keşfedilmiştir. Kimyager elektrik ile ilgili yaptığı deneyler sırasında oluşan kokuya, Yunancada koklamak anlamına gelen ozein kelimesinden türetilen ozon adını vermiştir (Alvim-Ferraz vd., 2024). Amerikan Gıda ve İlaç Dairesi tarafından 1997 yılında güvenli kabul edilen ajanlar grubuna alınan ozon, 2001 yılında yine aynı kurum tarafından uygun oranlarda kullanıldığında "gıdalarla doğrudan temasında sakınca yoktur" kararıyla, birçok sektörde yaygın olarak kullanılmaya başlanmıştır (Ong ve Ali, 2015). Ozonun bahçe ürünlerinin derim sonrası kalitesi üzerine etkisi, ozonun uygulama tipine (suda çözünmüş veya gaz formunda) ve dozuna (tek yüksek doz, sürekli veya aralıklı), ürün tipine ve meyvedeki mikrobiyal yüke bağlı olarak değişmektedir (Koyuncu vd., 2023). Bu nedenle uygun doz, uygulama tipi ve uygulama yapılacak ürünün fizyolojik özelliklerine dikkat edilmesi, ozon uygulamasından beklenen sonuçların alınmasında en önemli adımı oluşturmaktadır. Molekül halindeki ozon veya ozonun ayrışan ürünleri, herhangi bir kalıntı bırakmaksızın mikroorganizmaları hızlı bir şekilde inaktive edebilmektedir (Mahapatra, 2005). Ozon, mikroorganizmalarla temas ettiğinde, hücre zarında bulunan glikoproteinler, glikolipidler, lipoproteinler ve enzimlerle reaksiyona girmektedir. Bu reaksiyon sonucunda okside olan hücre zarı bozulmakta ve hücre içi bileşenleri dışarı sızarak hücrenin parçalanmasına neden olmaktadır. Bu nedenle, derimden sonra paketleme evine gelinceye kadar olan süreçte ya da depolamadan hemen önce bahçe ürünlerine yapılacak ozon uygulamaları, ürün üzerinde oluşması muhtemel bakteri, mantar ve maya kaynaklı istenmeyen mikroorganizma yükünü minimize edebilmektedir. Ozon uygulamaları havaya (ortama) ozon gazı vermek veya ozon gazını su içine enjekte etmek (çözmek) şeklinde yapılabilmektedir. Gaz halindeki ozon, ürünün içinde bulunduğu ortama (depo) sürekli veya aralıklı olarak uygulanabilirken, sulu formda ise ozon derimden hemen sonra veya yıkama işlemi sırasında uygulanabilmektedir. Suda ozon uygulamaları, çözünmüş ozon içeren suyu daldırma, ozonlanmış suyu püskürtme veya ozonlanmış suyla durulama şeklinde yapılabilmektedir (Sarron, vd., 2021).

2. BİTKİLERDE REAKTİF OKSİJEN TÜRLERİ VE ANTİOKSİDAN MADDELER

Bitkiler, gelişimleri boyunca virüs, fungus ve bakteri gibi biyotik; sıcaklık, kuraklık, radyasyon ve tuzluluk gibi abiyotik stres koşullarına maruz kalmaktadır (Wang vd., 2025). Doğaları gereği stres koşullarından uzaklaşma durumları olmayan bitkiler, bu olumsuz koşullara karşı koyabilmeleri için stres toleransı, stres adaptasyonu ve stresten kaçınma mekanizmalarını içeren gelişmiş moleküler savunma yeteneklerine sahiptir (Büyük vd., 2012; Torlak, 2019). Bitkiler kloroplast, mitokondri ve peroksizomlarda meydana gelen çeşitli metabolik reaksiyonlar sonucunda reaktif oksijen türleri (ROS) oluşmaktadır (Van Breusegem ve Dat, 2006). ROS'lar, hücre içi konsantrasyon seviyelerine bağlı olarak bitki hücrelerinde ikili bir role sahiptir. Düşük seviyelerde bulunduklarında hücre içi sinyal molekülleri olarak işlev görerek antioksidan sistem üzerinde düzenleyici ve olumlu etkiler göstermektedir (Waszczak vd., 2018). Bitki gelişimi sırasında sentezlenen düşük miktardaki ROS'lar, hücrenin detoksifikasyon mekanizmaları sayesinde zararlı bir etki oluşturmazlar. Buna karşın, yüksek konsantrasyonlarda biriken ROS formları toksik hale gelmekte ve nükleik asitler, proteinler ve lipitler gibi çeşitli organik moleküllerle etkileşime girerek oksidatif hasara ve sonuçta programlı hücre ölümüne neden olmaktadır (Sharma vd., 2012; Nilofar vd., 2024). Oksidatif stres altında yaşamlarını devam ettirebilmek ve stresle başa çıkabilmek için bitkiler, ROS'un kontrolü ve detoksifikasyonunu sağlayan çeşitli antioksidan sistemleri bulunmaktadır. Artan stres faktörleri ROS miktarındaki arttırmakta ve antioksidan savunma sistemleri ile ROS'lar arasındaki dengenin bozulmasına neden olmaktadır. Bu bağlamda, buradaki temel sorun serbest radikallerin üretimi değil; stres gibi ekstrem koşullar altında anormal ve aşırı miktarlarda üretilmeleridir.

2.1. Reaktif Oksijen Türleri

Reaktif türler geniş bir terim olup ROS, reaktif azot türleri (RNS) ve reaktif kükürt türlerini (RSS) kapsamaktadır. Bu türlerin bir kısmı serbest radikal yapıda olup, hücre içinde radikal süpürücü kapasitelerini aşan seviyelerde birikmeleri sonucu oksidatif strese neden olma potansiyeline sahiptir (Mittler, 2017). ROS, reaktif türler arasında en önemli grubu oluşturmakta ve serbest radikallerin yanı sıra eşleşmemiş elektronları bulunmayan ancak oldukça reaktif olan ve radikal olmayan formları da içermektedir. Hücrelerde bilinen başlıca ROS bileşikleri (Çizelge 1) arasında süperoksit radikali (O_2•−), hidroksil radikali (•OH), organik alkoksi (RO•) ve organik peroksil radikalleri (ROO•) (Gill ve Tuteja, 2010) ile radikal olmayan türleri ise singlet oksijen ($^1O_2$), hidrojen peroksit (H_2O_2) ve ozon (O_3) yer almaktadır (Dumont ve Rivoal, 2019). Hücredeki en reaktif oksijen türlerinden biri olan •OH, enzimatik bir detoksifikasyon mekanizmasına sahip olmadığından çevresindeki biyolojik moleküllerle ayrım gözetmeksizin reaksiyona girebilmekte ve aşırı miktarda üretildiğinde ise hücre ölümüne yol açmaktadır (Büyük vd., 2012). Buna karşılık, O_2•− ve H_2O_2, diğer ROS'lara kıyasla daha seçici reaksiyon göstermektedir.

Çizelge 1. Hücrelerde bilinen başlıca reaktif oksijen türleri

ROS türü	Özellikleri	Savunma mekanizması	Kaynak
Hidrojen peroksit (H_2O_2)	Hücrede savunma sisteminin başlaması, gen aktivasyonu, büyüme sinyali gibi olaylarda sinyal görevi görür. Hücrede miktarının yüksek olması lipid peroksidasyonuna, DNA hasarına ve protein oksidasyonuna sebep olabilir.	Katalaz (CAT) Askorbat peroksidaz (APx) Glutatyon peroksidaz (GPx) Savunma enzimleridir.	Quan vd., (2008)
Hidroksil radikal (•OH)	Hücre duvarı esnekliği, tohum çimlenmesi gibi bitki gelişiminde olumlu katkılar sağladığı bilinmektedir. Ancak en reaktif ve toksik ROS olması sebebiyle hücrede miktarındaki artış lipit peroksidasyonuna, DNA hasarına ve hücre ölümüne neden olabilir.	Detoksifikasyonun da doğrudan görev alan bir enzim sistemi bulunmamaktadır.	Richards vd., (2015)
Singlet oksijen ($^1O_2$)	Bitkiler, klorofil açısından zengin oldukları ve $^1O_2$ yapraklarda sürekli üretildiği için $^1O_2$'nin neden olduğu oksidatif strese maruz kalmaktadır. Singlet oksijen, D1 proteininin degradasyonuna neden olarak fotosistem II aktivitesinin ışık kaynaklı kaybından sorumlu olan en önemli ROS olarak kabul edilmektedir. Ayrıca pigmentlerin "ağarması" veya "beyazlaşmasına" sebep olmaktadır.	Karotenoidler ve α-tokoferol tarafından detoksifikasyonu sağlanabilir.	Xie vd., (2019)
Süperoksit anyonu (O_2^-)	Orta reaktivite, kısa ömürlüdür. Hücre içerisinde aşırı birikirse oksidatif hasar oluşturma potansiyeli vardır.	SOD enzimi tarafından detoksifikasyonu sağlanır.	Phua vd., 2021

Radikaller ile biyolojik moleküller arasındaki etkileşimi önleyebilmek için antioksidanların, radikalin oluştuğu bölgenin yakınında olması ve biyolojik substratlarla serbest radikaller arasında rekabet edebilmesi gerekmektedir (Arora vd., 2002). Antioksidanların ROS'u nötralize edecek yeterli miktarda bulunmaması durumunda lipit peroksidasyonu, protein hasarı (aminoalkanoik asit kalıntılarının karbonillenmesi), DNA ve RNA oksidasyonu, enzim inhibisyonu ve apoptoz aktivasyonu gibi biyomoleküllerde hasarlar meydana gelmektedir (Gill ve Tuteja, 2010). ROS'lar genel olarak zararlı moleküller olarak değerlendirilse de hücresel sinyal iletiminde önemli görevler üstlendikleri bilinmektedir (Waszczak vd., 2018; Sood, 2025). Bitkilerde ROS'lar, büyüme, gelişme, doku farklılaşması, kök gelişimi, tohum çimlenmesi ve yaşlanma gibi süreçlerin düzenlemesinde görev almaktadır. Stres koşullarında kontrollü ve düşük konsantrasyonlarda biriken ROS'lar, savunma sinyalleri olarak işlev görerek antioksidan enzim sistemlerinin aktivasyonunu ve stres toleransının artmasını tetiklemektedir (Sood, 2025).

2.2. Bitki Antioksidan Savunma Sistemleri

Antioksidanlar, hücreleri serbest radikaller adı verilen zararlı moleküllerin neden olduğu hasardan korumaya yardımcı olan bileşiklerdir. Oksidatif zararı azaltmaya yardımcı oldukları için birçok sistemde çok önemlidir (Göçer vd., 2013; Çakmakçı vd., 2015). Aşırı oksidasyon seviyesi ve hücre bileşenlerinin indirgenmesi bitki için zararlıdır, bu yüzden redoks homeostazını korumak hücre için çok önemlidir (Foyer ve Shigeoka, 2011). Bundan dolayı bitkiler antioksidan aktiviteye sahip bileşikler açısından son derece zengindir. Antioksidatif savunma sistemleri türden türe farklılık gösterse de her bitki dokusu içerisinde mevcuttur (Wachter vd., 2005; Pulido vd., 2009). Tanımı gereği antioksidanlar, serbest radikal reaksiyonlarını inhibe edebilen ve hücre hasarını geciktirebilen veya önleyebilen molekülleri temsil ederler ve oksitlenebilecek potansiyeldeki substratları oksidasyonunu önemli ölçüde geciktiren veya engelleyen moleküllerdir (Nimse ve Pal, 2015; Dumont ve Rivoal, 2019).

Daha düşük konsantrasyonlarda bile oksidasyona karşı mücadele edebilen antioksidanlar, enzimatik ve enzimatik olmayan antioksidanlar olmak üzere iki kısımda incelenmektedir. Bitkilerin, hücre savunma sisteminde ROS'ların temizlenmesinde aktif rol alan düşük nispi moleküler kütleli enzimatik antioksidanlar suda-çözünebilen bileşiklerden olan askorbat, glutatyon ve fenoller ile yağda-çözünebilen tokoferoller, tokotrienoller ve karotenoidlerdir. Bu enzimatik olmayan bileşikler reaktif oksijen türleri ile kendi kendine reaksiyona girebilir, ancak süperoksit dismutaz (SOD), katalaz (CAT) askorbat peroksidaz (APX) ve glutatyon peroksidaz (GPX) gibi enzimatik antioksidanların reaksiyon detoksifikasyon verimliliği daha yüksektir (Noctor ve Foyer, 2016; Noctor vd., 2018). Enzimatik antioksidanlar ve enzimatik olmayan antioksidanlar farklı şekillerde çalışarak oksidatif stresin etkilerini sınırlandırmaktadırlar.SOD, oksidatif stres anında ilk savunma hattı olarak görev yaparak $O_2{\bullet}{-}$'nin hızlı dismutasyonunu katalize etmekte ve nispeten daha az zararlı ve stabil olan H_2O_2'ye dönüştürmektedir. Böylece •OH oluşumunu azaltarak oksidatif stresi hafifletmede ciddi bir rol oynamaktadır. SOD katalizli dismutasyon reaksiyonları kendiliğinden oluşan reaksiyonlardan 10.000 kat daha hızlı çalışmaktadır. SOD enziminin Cu/Zn SOD, Mn-SOD ve Fe-SOD olmak üzere 3 farklı izoenzim formu bulunmaktadır (Zheng vd., 2023). Bu izoenzimler H_2O_2 ve potasum siyanür'e karşı hassasiyetlerine göre farklılaşmaktadır (Bannister vd., 1987). Hücre içerisindeki çeşitli metabolik faaliyetlerde sinyal görevi gören H_2O_2 dengede tutulmasında hem koruyucu hem de düzenleyici olarak yer alan en önemli enzimlerden birisi CAT'dır (Mhamdi vd., 2010). Hücre organelleri göz önünde bulundurulduğunda CAT peroksizomlarda yüksek miktarlarda bulunmaktadır (Joseph ve Jini, 2010). CAT, oksidasyon sırasında iki H_2O_2 molekülünün indirgeme eşdeğerine ihtiyaç duymadan su ve oksijene ayrışmasını katalize etmekte benzersiz bir yeteneğe sahip olduğundan H_2O_2 detoksifiye etme konusunda oldukça etkilidir (Arora vd., 2002). APX ilk sınıf peroksidaz enzimi olarak değerlendirilir ve APX enziminin sAPX, tAPX, mAPX, cAPX ve mitAPX olmak üzere 5 farklı izoenzim formu hücre organellerine dağılmış durumda bulunması sayesinde APX enziminin bitki hücresi için önemli olduğu belirlenmiştir (Jimenez vd., 1997; De Leonardis vd., 2000). Çeşitli çevresel streslere yanıt olarak ortaya çıkan bu izoenzim formları, antioksidanlar arasındaki iletişimin kurulmasında önemli bir rolü bulunmaktadır (Veljović-Jovanović vd., 2018). APX enzimi normal metabolik süreçlerde oluşan düşük düzeydeki H_2O_2'yi kontrol altında tutarak aşırı birikimini önler ve hücrenin korunmasında görev alır (Pandey vd., 2017). H_2O_2'ye karşı güçlü bir aktiviteye sahip olan diğer enzim GPX'dir. Bitki hücrelerindeki fizyolojik işlevleri bakımından GPX ligninin biyosentezi, indol-3-asetik asit adlı bitkisel hormonun parçalanması ve biyotik stres faktörlerine karşı H_2O_2'nin detoksifikasyonunda görev almaktadır (Herbette vd., 2002). GPX enzimi kuraklık, ağır metal toksisitesi, aşırı sıcaklık ve tuzluluk gibi stres koşullarında artış göstererek ROS birikimini sınırlamada görev almaktadır (Fu, 2014). Enzimatik olmayan antioksidan maddeler arasında olan askorbik asit, çeşitli enzimatik ve enzimatik olmayan reaksiyonlar için elektron verme yeteneğine sahip olduğundan güçlü bir antioksidan kaynağı olarak kabul edilmektedir (Gegotek ve Skrzydlewska, 2023). Askorbat bitki dokularında farklılaşma, büyüme ve metabolizma gibi önemli süreçlerde rol oynamaktadır. Bitki hücrelerinde kantitatif olarak dominant bir antioksidan olan askorbat, potansiyel olarak zararlı dış pro-oksidanlara karşı birincil savunma hattı olarak kullanılmaktadır (Davey vd., 2000). Askorbat, •OH, $O_2^{\bullet-}$ ve $^1O_2$'yi doğrudan yakalayabilir ve ayrıca APX enzimi aracılığıyla H_2O_2'yi suya indirgeyebilmektedir (Noctor ve Foyer, 1998). Glutatyon, bitkilerde stres anında savunma mekanizmasını etkileyen en önemli antioksidan olmayan enzimlerden biridir (Hasanuzzaman vd., 2017), fakat glutatyon'un oksidatif strese karşı görev alabilmesi için indirgenmiş formda bulunması gereklidir. İndirgenmiş formdaki glutatyon önemli bir kükürt depo formu olarak kullanılabilmektedir ve hücresel büyüme, gelişme, kükürt taşınmasının regülasyonunda, sinyal iletimi, protein ve nükleik asit sentezi ve strese neden olan genlerin ifadesi de dahil olmak üzere çeşitli biyolojik süreçlerde önemli roller oynamaktadır (Bartoli vd., 2017). Bu önemli rollere ek olarak, glutatyon'un ana rolü glutatyon-askorbat döngüsü aracılığıyla başka bir güçlü hidrofilik antioksidan olan askorbik asidi rejenere etme yeteneğidir (Sharma vd., 2012). Bitkilerde yaygın olarak bulunan ve güçlü antioksidan kapasiteleri ile ilişkilendirilen fenolik bileşikler, serbest radikalleri detoksifiye etmek için çok uygun olan yapılar içermektedir. Bu bileşikler, $^1O_2$'yi direkt detoksifiye etmekte ve lipit alkoksi radikallerinide detoksifiye ederek lipit peroksidasyonunu inhibe etmektedir (Sharma vd., 2012). Tokoferoller hem antioksidan hem de antioksidan olmayan işlevlerde görev aldıkları için hücre membranının temel bileşenleridir. Tokoferoller, lipofilik antioksidanların bir üyesidir ve fotosentetik organizmalar tarafından sentezlendikleri için bitkinin yalnızca yeşil ve fotosentetik olarak aktif kısımlarında bulunmaktadır. Bu yüzden, kloroplastlardaki $^1O_2$'yi detoksifiye edilmesinde tokoferoller antioksidan olarak görev almaktadır. Ayrıca, lipitleri ve diğer membran bileşenlerini ve fotosistem yapısını ve performansını korumaktadır (Sharma vd., 2012). Sarı, turuncu ve kırmızı renk oluşumlarından sorumlu olan likopen, β-karoten, ksantofil, lutein ve zeaksantin gibi karotenoidler, reaktif oksijen türlerini detoksifiye edebilen ve lipid peroksil radikalini en etkili şekilde yakalayarak hücre membran koruması sağlayan lipofilik antioksidanlardandır. Karotenoidler bitki dokularındaki fotosentetik bileşenleri korumak için $^1O_2$ detoksifiye edebilmektedir. Bu yüzden, karotenoidler, fotosentetik aktiviteyi koruduğu için enzimatik olmayan antioksidanlar sınıfında yer almaktadır (Kehrer, 2000; Sharma vd., 2012).

3. OZON UYGULAMALARININ ANTİOKSİDAN ENZİM AKTİVİTELERİ ÜZERİNE ETKİSİ

Ozon uygulamaları ile ilgili dikkat çeken noktalardan birisi, kontrolsüz kullanıldığında ozonun oksitleyici etkisi sebebiyle ROS oluşumu tetikleyerek, savunma mekanizmasını ve antioksidan enzim aktivitesini değiştirebilme ihtimalidir. Çünkü yüksek dozda veya sürekli uygulanması, dokularda oksidatif hasara veya fitotoksiteye neden olarak enzim aktivitesinin azalmasına yol açabilmektedir (Zhang vd, 2020; Botondi vd., 2021). Son yıllarda, bahçe ürünlerinde ozon uygulamalarının fiziksel ve kimyasal kalite özelliklerine katkılarının araştırılması yanında, metabolik faaliyetleri düzenleyen enzimler üzerine etkilerinin araştırıldığı çalışmalar da ön plana çıkmaya başlamıştır. Bu çalışmalarda, genel olarak ozon uygulamalarının enzimatik olan ve olmayan antioksidanlar üzerine olumlu katkılarda bulunduğu, böylelikle ürünlerinin savunma mekanizmasının güçlenmesiyle ROS'ların birikiminin önlendiği, olgunlaşma ve yaşlanmanın geciktiği ve dolayısıyla muhafaza süresinin uzadığı ifade edilmiştir. Ozon uygulamasının antioksidan maddeler üzerine etkisi; uygulama şekline, dozuna ve ürün tipine bağlı olarak değişse de genel olarak değerlendirildiğinde ozonun pozitif etkisi belirgindir (Çizelge 2). Ozon uygulamalarının, kivide SOD ve CAT aktivitesini arttırdığı (Piechowiak vd., 2022), pitayada SOD, CAT gibi antioksidan enzimlerinin aktivitesini düzenleyerek ROS seviyesindeki hızlı artışı önlediği (Li vd., 2023), çileklerde süperoksit radikal anyonlarının üretim oranını düşürdüğü ve hidrojen peroksit (H_2O_2) içeriğini, süperoksidaz (SOD), katalaz (CAT), askorbat peroksidaz (APX) ve monodehidroaskorbat redüktaz (MDHAR) aktivitesini artırdığı belirlenmiştir. Ayrıca askorbik asit (ASA), glutatyon (GSH) ve ferrik indirgeyici/antioksidan aktiviteyi teşvik ettiği rapor edilmiştir (Zhang vd., 2020).

Çizelge 2. Ozon uygulamalarının ürünlerin antioksidan savunma sistemleri üzerine etkisi

Ürün	Uygulama dozu ve yöntemi	Sonuç	Literatür
Papaya	0, 1.5, 2.5, 3.5 ve 5.0 µL L^{-1} Gaz formda sürekli	PAL, POD ve PPO enzim aktivitelerini arttırdığı, solunum hızı ve etilen üretim miktarını baskıladığı, antioksidan savunma mekanizmasının etkinliğini arttırdığı belirlenmiştir.	Ong vd., (2014)
Armut	2.14, 6.42 ve 21.4 mg m^{-3} Gaz formda Her gün 1 saat	SOD, CAT, POD ve PPO enzim aktivitelerini düzenlediği, antioksidan aktiviteyi arttırdığı ve yumuşamayı geciktirdiği rapor edilmiştir.	Zhao vd., (2013)
Mango	1 mg L^{-1} s^{-1} 10 ve 20 dk Suda uygulama	Meyve kalitesini korunduğu belirlenmiş ancak antioksidan potansiyeli olan maddeler (askorbik asit, dehidroaskorbik asit, β-karoten ve toplam fenolik madde miktarı) üzerine net bir etkinin saptanmadığı ifade edilmiştir.	De Almeida Monaco vd., (2016)
Kivi	10 ve 100 ppm Gaz formda	Kalitenin korunması, SOD ve CAT enzimlerinde artış, daha düşük ROS	Piechowiak vd., (2022)
Armut	1 ppm Gaz formda	Ozon uygulanmış armutlarda ROS üretiminin ve lipid peroksidasyonunun azaldığı; SOD, CAT, POD gibi enzim aktivitelerinin ise artığı bildirilmiştir.	Lin vd., (2024)
Yaban mersini	15 ppm Gaz formda	SOD, GPx, PAL aktiviteleri artmış; ROS seviyesi azalmıştır.	Piechowiak vd., (2020)
Üzüm	12 saat Gaz formda	CAT, APX, GPX ve SOD aktivitelerini arttırdığı, PPO'yu ise düşürdüğü bildirilmiştir.	Modesti vd., (2018)
Çilek	10.72 mg m^{-3} Gaz formda	SOD, CAT ve APX enzim aktivitelerinin artırıldığı bildirilmiştir.	Zhang vd., (2020)
Mandarin	200 µL L^{-1} Gaz formda	SOD, CAT ve APX enzim aktivitelerini artırdığı bildirilmiştir.	Boonkorn vd., (2012)

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GENETIC RESOURCE MANAGEMENT IN VEGETABLES: *IN SITU* AND *EX SITU* CONSERVATION OF LOCAL VARIETIES AND GENOTYPIC VARIATION

Andaç Kutay SAKA[1]

1. INTRODUCTION

Horticultural crops play an important role in revitalizing rural economies as high-value products (Kang et al., 2025). Horticultural crop production is particularly attractive for small-scale farmers. Research is being conducted on important horticultural crops for the purpose of collecting, conserving, and evaluating genetic resources in horticultural crops. Collected genetic materials should be used for sustainable variety development studies and to prevent the extinction of these materials. Garden plants, which constitute a significant part of plant genetic resources in agricultural production, include fruits, vegetables, root and tuber vegetables, vines, and ornamental plants. Important horticultural crops include hazelnuts (Karakaya et al., 2023; Yılmaz et al., 2024), apples (Karatas, 2021), walnuts (Başak et al., 2022), cherries (Demir et al., 2011), peach (Asma and Öztürk, 2005), tea (Islam et al., 2024), chestnut (Serdar et al., 2014), grapevine (Çelik et al., 2008; Aydemir and Göksu, 2023; Kesgin et al., 2025), tomato (Henareh and Dursun, 2015; Öztürk, 2022; Saka, 2023), pepper (Bozokalfa and Eşiyok, 2011), eggplant (Uysal et al., 2023), watermelon (Şahin, 2024), melon (Yıldız et al., 2011), squash (Şavkan et al., 2025), onion (Cebeci

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et al., 2021), garlic (Uğur et al., 2021; Kıraç et al., 2022), white cabbage (Balkaya et al., 2005), and rose (Oğraş et al., 2017).

The diversity of existing genetic resources, the result of approximately 10,000 years of effort, forms the basis of today's modern, high-yielding, disease-resistant, high-quality, and nutrient-rich crop varieties. Plant genetic resources have been used in various ways since the dawn of human civilization for food, clothing, shelter, energy, animal feed, fiber, medicine, etc. (Rajpurohit and Jhang, 2015). Rapid global population growth poses significant obstacles to meeting basic human needs such as shelter, food security, access to education, and general health. Due to domestication efforts and subsequent developments, genetic diversity has declined among commonly cultivated plant species. Limited genetic diversity poses an obstacle to plant breeding, especially under changing environmental conditions (Bal et al., 2025). To alleviate this problem, wild relatives, which are the wild equivalents of domesticated plant species, are being studied and used more frequently (Dempewolf et al., 2017). Due to their close genetic relationship with cultivated species, wild plant species serve as reservoirs of important genetic traits for plant evolution (Guarino and Lobell, 2011). Plant genetic resources for food and agriculture include modern varieties, breeding lines and germplasm stocks (a variety or line known to possess one or more specific traits), landraces, ecotypes, local varieties, and wild relatives of cultivated plants (Figure 1). Breeding stocks, wild relatives of cultivated plants, and landraces are among the most important resources for developing new plant varieties (Tan, 2010; Taş et. al., 2017; Suma et al., 2025). In general, there is a consensus that local varieties are genetically heterogeneous despite their outwardly homogeneous appearance (Camacho Villa et al., 2005). Although it is difficult to define local varieties precisely, two types of definitions are used for local varieties (Maxted et al., 2013).

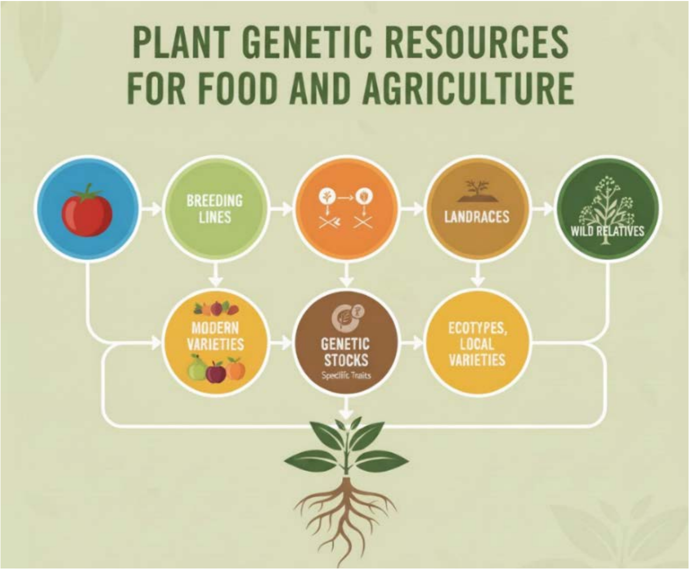

Figure 1. Plant genetic resources for agricultural cultivation systems

First, they are dynamic populations of cultivated crops that are typically genetically distinct, have not undergone formal plant breeding processes, are adapted to local conditions, integrated into traditional farming systems, and have a historical background (Camacho Villa et al., 2005). Second, a local variety of a seed-propagated plant can be defined as a recognizable variable population, often with a local name. Therefore, local varieties are not included in official plant breeding programs, have high specific adaptations to the environmental conditions (tolerance to biotic and abiotic stresses) of the region where they are grown, and are closely related to the celebrations, dialect, customs, knowledge, and traditional uses of the people who developed and continue to cultivate these varieties (Negri, 2003). Local varieties, which are an invaluable resource for agricultural production, combating climate change, and food security, are increasingly under threat, and genetic erosion is increasing (Giorgi and Porfiri 1998, Ishikaw et al., 2006, Tsegaye and Berg

2007). In recent years, the preference for certain types of crops in agriculture has led to the risk of extinction of plant species that are not preferred (Haspolat et al., 2016; Salgotra and Chauhan 2023). Therefore, it is essential to protect local diversity in a systematic, coordinated, and integrated manner using *in situ* (conservation of diversity in its natural habitat) and *ex situ* (conservation outside its natural habitat) techniques. The continuity of agricultural production is possible thanks to increasing technology and a better understanding of plant structures. At this stage, the conservation of genetic resources is important (Gross et al., 2014). Two main strategies are used to protect biological diversity in all agricultural production systems: *ex situ* and *in situ* conservation, both of which are considered equally important and complementary to each other (Maxted et al., 1997; Dulloo et al., 1998; Engelmann and Engels 2002; Dulloo et al., 2010).

2. *IN SITU* CONSERVATION

In situ conservation is one of two fundamental strategies developed to prevent the loss of biological diversity and refers to the preservation of genetic diversity within ecosystems where species inhabit their natural habitats (Aykas et al., 2018). The main objective of this approach is to ensure that species maintain their existence in the natural habitats where they preserve and develop their distinctive characteristics. At the same time, *in situ* conservation allows the evolutionary process to continue thanks to the ongoing interaction between plants and the environment (Tan, 2010). *In situ* conservation strategies for vegetable genetic resources are divided into two main approaches, depending on the type of ecosystem where conservation takes place.

2.1. Conservation in Natural Habitats

This approach aims to protect wild species, their wild relatives, and natural flora in natural environments that are isolated from human influence as much as possible or specially managed (Rajpurohit and Jhang 2015). Thus, wild species, which are of great importance in vegetable variety development and parent plant production, will be protected by isolating them from negative factors. Protected areas and nature reserves are established that allow species to remain within their natural ecological continuity (natural or appropriately maintained), thereby ensuring the creation of protected areas.

2.2. Conservation in Agricultural Ecosystems (Conservation Under Farmer Conditions)

This approach involves maintaining agricultural biodiversity and genetic resources in areas where farmers have long cultivated them using traditional methods, namely in open fields and their home gardens (Karagöz et al., 2025). This is also referred to as “on-farm” conservation. The conservation of local varieties, which have been cultivated by farming families for thousands of years and are adapted to the ecological conditions of their region, is essential. Local varieties have a moderate yield capacity even under low input conditions and can tolerate biotic and abiotic stress conditions to a high degree (Karagöz, 2014). The *in situ* method protects not only genetic material but also the treasure trove of “traditional agricultural knowledge” passed down from generation to generation regarding the use, cultivation techniques, and preservation of these products, thereby ensuring the transfer of traditional knowledge (Karagöz et al., 2025). Furthermore, farmer-based conservation programs aim to expand farmers' participation in the conservation of agricultural biodiversity and increase the use of these resources for local livelihoods, thereby ensuring sustainable development integration (Tan, 2002; Tan, 2009). In conclusion, *in situ* conservation provides a complementary and reliable conservation method against the threat of genetic erosion that *ex situ* conservation methods (such as seed gene banks or tissue culture) cannot overcome alone, by ensuring the continuity of evolutionary adaptation in natural environments.

3. *EX SITU* CONSERVATION

By definition, *ex situ* conservation is the protection of biodiversity elements such as seeds, living plants, living tissue, cells, and/or DNA material outside the natural habitats of populations that are threatened or need to be collected and protected (UNCED, 1992). The general advantages provided by *ex situ* conservation are: the preservation of genetic diversity; the ease with which scientists and breeders can readily use the preserved genetic material to develop new and superior varieties with traits such as resistance to disease, pests, drought, or heat; it serves as a critical reservoir against damage that cannot be prevented by *in situ* conservation, and it offers the only feasible conservation method for species that are difficult or impossible to conserve under *in situ* conditions (e.g., species that do not produce seeds or have short-lived seeds). *Ex situ* conservation methods span a wide spectrum, including gene banks, field gene banks, *in vitro* storage banks, cryopreservation, pollen banks, DNA banks, botanical gardens, and medicinal and aromatic plant gene banks. However, seed gene banks are the most common storage method for conserving the genetic resources of vegetable species.

3.1. Seed Gene Banks

There are numerous gene banks located in different regions of the world (the United States, Europe, Asia). Gene banks play a vital role in the discovery, collection, conservation, and scientific dissemination of plant genetic diversity, which is essential for improving crops for food, health, and nutrition security (Rajpurohit and Jhang, 2015). A large proportion of the species preserved in gene banks consist of plant species that form the basis of human and animal nutrition (FAO, 2014). Among the world's major seed gene banks are the United States Department of Agriculture (USDA) in the USA, the French National Institute for Agricultural Research (INRA) in France, the Asian Vegetable Research and Development Center (AVRDC) in Taiwan, the National Seed Gene Bank (NBPGR) in India, which holds a large number of vegetable materials including tomatoes, peppers, okra, and various cucurbits, the Svalbard Global Seed Vault in Norway, located in Germany and containing 17,861 accessions of important vegetable species (tomato, pepper, eggplant, carrot, spinach, *Allium*, *Brassica* and the lettuce) the German Federal *Ex situ* Gene Bank for Agricultural and Horticultural Plants and the Vavilov Institute in Russia. Vegetable species account for 6.6% of the materials preserved in gene banks (FAO, 2023). In our country, the National Seed Gene Bank operates internationally within the Aegean Agricultural Research Institute (ETAE) in Izmir. This bank is a pioneering institution that has gained significant experience in *ex situ* conservation since the 1960s. As of 2023, 11.340 of the 57.767 seed samples stored in the ETAE National Seed Gene Bank are vegetable materials. Among the vegetable seed samples in the National Seed Gene Bank, the most represented plant species are *Capsicum* spp., *Cucurbita* spp., *Solanum lycopersicum*, *Cucumis melo*, *Hibiscus esculentus* and *Citrillus* spp. vegetable species (Binbir et al., 2024).

Seeds are dried to low moisture content and stored at low temperatures without losing their viability. Seed banks are one of the most commonly used techniques in the *ex-situ* approach to conservation (Aykas et al., 2024). When seeds are dried to low moisture content and stored at low temperatures (-18°C or below), they can be preserved for many years (up to 30 years in the medium term and up to 100 years in the long term) without losing their viability (Aykas et al., 2016; Panis et al., 2020). Furthermore, seed gene banks offer storage convenience, space savings, relatively low labor requirements, and the capacity to preserve a large number of seed samples at a reasonable cost (Aykas et al., 2018). As forms of plant seeds used as genetic resources, they also provide a suitable and practical means for the use and international exchange of collected genetic material.

3.2. *In vitro* Storage

Modern biotechnological methods offer significant advantages in the conservation of species at risk of extinction, overcoming the challenges faced by traditional conservation methods (such as the need for large areas and propagation problems) (Bürün, 2021). *In vitro* propagation and conservation methods, i.e., modern methods, can be applied to vegetatively propagated species, species with short-lived seeds that are not tolerant to desiccation, and some species that encounter different problems (Paunescu, 2009; Pandotra and Gupta, 2015; Oseni et al., 2018). *In vitro* methods for the conservation of genetic resources are used for short- or medium-term preservation. The *in vitro* storage of plant material is usually achieved by slowing down growth. This is done by altering the culture medium composition (reducing mineral or sugar concentration) or environmental conditions (low temperature/light) (Rajasekharan and Sahijram, 2015). In this way, genetic materials can be preserved for several months to two to three years without subculturing (Vasile et al., 2011).

3.3. Cryopreservation

This is a vital method for long-term preservation and involves storing plant material (buds, meristems, embryos, etc.) at ultra-low temperatures, typically in liquid nitrogen (-196°C)

(Kulus, 2019; Dinato et al., 2020; Tirado-Perez and Sandoval-Cancino, 2022). At this temperature, all metabolic processes and cell divisions are halted, theoretically allowing genetic material to remain unchanged indefinitely (Fiona, 2021). This method is particularly important for the conservation of species that are clonally propagated (vegetative) or have recalcitrant seeds.

3.4. DNA Banks

In this method, genetic information is preserved at the molecular level, and DNA samples are stored under appropriate conditions. DNA banking is an effective, simple, long-term, and evolving technique for preserving genetic information. However, there are some issues in practice related to gene isolation, cloning, and the reintroduction of DNA into a plant. The development of standard storage protocols is necessary for this technique (Van Treuren and Van Hintum, 2014).

4. UTILIZING VEGETABLE GENETIC VARIATIONS IN NEW VARIETY DEVELOPMENT STUDIES

The use of vegetable genetic resources in new variety development is of vital importance for ensuring the sustainability of agricultural production and responding to global challenges. Vegetable genetic resources are an indispensable genetic source for breeding programs, as they enable the development of new varieties with superior qualities (Salgotra and Chauhan 2023; Khan, 2024; Teo and Yu 2024). The primary function of vegetable genetic resources is to provide the genetic diversity necessary for developing new varieties that are resilient, productive, and high-quality in the face of challenging conditions such as climate change, diseases, pests, and abiotic stresses (Naqvi et al., 2022; Kapazoglou et al., 2023; Fraooq et al., 2025). Türkiye's rich vegetable genetic resources are extensively used in both open-pollinated and hybrid variety breeding studies (Binbir et al., 2024). The genetic diversity possessed by our country's local varieties and wild relatives forms the basis for breeding studies and is important in conferring resistance to abiotic/biotic stress factors. Varieties developed in important vegetable species using vegetable genetic resources in Turkey have been developed. These varieties include Ege Pembesi 50, 1915 (Çanakkale Tomato), Menemen (open-pollinated varieties), and MASS 1001 F1 (hybrid variety) in tomatoes; Bağcı Çarliston, Ege 91, Ege Acı Sivri, Uraz 98, Menderes, Seyrek, Aybar, Sare, and Arın; in eggplant, Topan 374, Kemer 27, Aydın Siyahı 55, Halep 18, and hybrid varieties Fener F1, Hisar F1, Karun F1, in melon; Kırkağaç 637, Kırkağaç 589, Hasan Bey, Çinikız 98, Çeşme 2003, in lettuce; Yedikule 5701 and Zümrüt, and in okra; Bornova 2003 varieties have been developed (Binbir et al., 2024). Over the past 10 years, studies have been conducted on the morphological characterization of a total of 447 samples, including 289 populations of tomato (*Solanum lycopersicum* L.), 110 populations of pepper (*Capsicum annuum* L.), and 48 populations of eggplant (*Solanum melongena* L.) (Binbir 2017, Binbir et al., 2018, 2022).

5. FUTURE PROSPECTS

To record genetic erosion and changes in species populations, plant genetic resources should be assessed at regular intervals. In this process, it is recommended to use modern tools such as Geographic Information Systems (GIS) to monitor and map genetic erosion and to develop early warning systems (Rajpurohit and Jhang, 2015). The current status should be determined by conducting new surveys in areas that have not been researched in the last 20 years, and new studies should be conducted on species and topics that have not been studied. Since modern agricultural practices often lead to a decrease in crop diversity, positive incentives should be provided to local communities and farmers to encourage them to preserve diversity. Furthermore, protecting the food and cultural practices that are part of these communities' survival strategies is a critical step in maintaining local diversity. In this context, agricultural programs must be integrated with projects that ensure rural development and livelihoods (Timberlake et al., 2024; Sithole and Olorunfemi 2024). Studies now show that simply collecting seeds is not effective; instead, focus must be placed on how to best utilize existing resources, the need for breeders to prioritize the collection and documentation of materials with specific “traits” (disease resistance, drought tolerance, etc.), Increasing the biochemical and molecular characterization of local varieties; strengthening the application of techniques such as gene pools and “core collections” (Swarup et al., 2021; Nguyen and Norton 2020; Engels et al., 2024). In the future, advances in sensor technology could optimize survival times by enabling individual control of seed moisture content and storage temperature (Weise et al., 2025). In addition, to increase scientific capacity, plant breeders and scientists should be provided with free training in inventorying, survey techniques, and genetic erosion studies to develop the skills of technical personnel. Furthermore, international connections should be strengthened for the conservation of genetic resources, and sustainable funding sources (such as the Global Crop Diversity Trust) should be used effectively for these activities. It is also recommended that issues such as the conservation of wild relatives be included in Environmental Impact Assessment (EIA) processes. In summary, efforts to conserve plant genetic resources can be likened to a vast digital library. The main goal for the future is not only to add new books (collect seeds) to the library, but also to index the contents of these books in detail (characterization) and ensure that researchers can easily access this information to write the resilient products of the future.

6. CONCLUSION

The effective management of vegetable genetic resources, particularly wild relatives and landraces, is of vital importance for global food security and adaptation to climate change. While modern breeding efforts have been successful in increasing yields, they have also led to a narrowing of genetic diversity and made plants more susceptible to biotic and abiotic stress factors. In this context, wild relatives of vegetables stand out as valuable genetic reserves harboring resistance and adaptation genes lost during the domestication process. *In situ* and *ex situ* conservation approaches are two complementary fundamental approaches to preserving this diversity. Seed gene banks serve as a critical "insurance" for the long-term preservation and accessibility of genetic material, while *in situ* conservation methods allow genetic material to continue its evolutionary adaptation to changing environmental conditions. However, simply collecting material is not enough; the lack of data (passport data, phenotypic and genotypic characteristics) in collections is one of the biggest obstacles limiting the use of these resources in breeding programs.

Consequently, the sustainable management of vegetable genetic resources is not merely a conservation activity; it is a strategy for building resilient agricultural systems for the future. The in-depth analysis of existing collections using modern biotechnological tools and the creation of new trait-focused collections will make agricultural production more sustainable and resilient to challenging environmental conditions.

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TÜRKİYE VE DÜNYADA

BAHÇE BİTKİLERİ YETİŞTİRME VE ISLAHI

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