BLUE ECOSYSTEMS AND SUSTAINABLE AQUATIC PRODUCTS: SCIENTIFIC APPROACHES FROM PAST TO PRESENT

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DUVAR

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Akdeniz'den Karadeniz'e: Türkiye Deniz Ekosistemlerindeki Mikroplastik Araştırmalarının Güncel Panoraması

Saniye TÜRK ÇULHA[1], Murat YABANLI[2], Mehmet ÇULHA[3]

Mikroplastik Kirliliğinin oluşturduğu tehdit, çevre, insan sağlığı, ekonomi ve doğal ortamda yaşayan diğer canlı türleri üzerindeki etkileri ile ilgili çok az veya hiç kolektif bilgi toplanmadan araştırılmıştı. Ancak artan tehdit ve sürekli büyüyen bir tehdit oluşturmaya başlayınca, kirlilik kaynağının birinci sırasında yer alan bir konu haline gelmiştir. Her yıl çevreye karıştığı tahmin edilen 20 milyon ton plastik çöpün 2040 yılına kadar önemli ölçüde artacağı düşünülmektedir. Plastik kirliliği, kara, tatlı su ve deniz ortamları dahil olmak üzere tüm çevresel ekosistemleri etkilemektedir. Bu artış biyolojik çeşitlilik kaybının ve ekosistem bozulmasının nedenlerinden biri olarak görülmektedir (IUCN 2025). Deniz ekosistemlerindeki plastiklerin ömrü uzun olduğu için, üretimleri ve bertarafları durdurulsa bile, deniz yaşamı üzerindeki olumsuz etkileri yıllarca devam edecektir (Avio et al. 2017). Plastik kirliliği dünya denizlerini tehdit ettiği kadar Türkiye denizlerini de tehdit etmektedir. Ülkemizde özellikle kıyısal alanlardaki yerleşim bölgeleri ve sanayi kuruluşlarının olumsuz etkileri çok fazla olmaktadır. Suların nehir, dere, körfez, koy, lagün vb. gibi alanlara arıtılmadan deşarj edilmesi, askıda katı madde yükü bakımından zengin kirli suyun direkt boşaltılması bu olumsuz etkileri daha fazla tetiklemektedir. Özellikle endüstri atıklarının alıcı ortam olarak düşünülen denizlere akıtılması bu kirliliği tetikleyen en büyük sorunların başında gelmektedir. Türkiye'deki mikroplastik kirliliğine genel bir bakış ile konuya dikkat çeken Yurtsever (2015)'in çalışmasıyla konuya gereken ilgi zamanla artmaya başlamış ve bugün aşağıda tablo halinde sunacağımız çalışmaların başlangıcı olmuştur. Deniz, nehir, atıksu, sahil çöpü, karasal alandaki canlılar, toprak ve havadaki mikroplastik kirliliği üzerine yapılmış birçok çalışma yer

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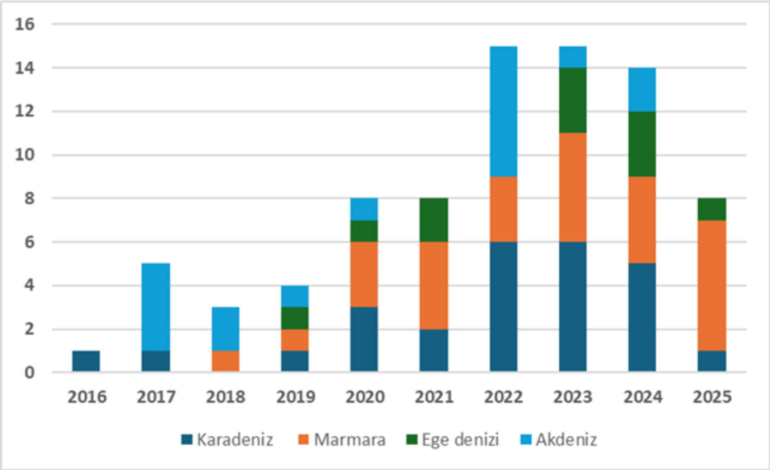
almaktadır. Bu derlemede ele alınan konular ise Türkiye denizlerinde yapılmış çalışmaları içermektedir.

Türkiye'de plastik kirliliği ile ilgili çalışmalar 2010 yılında ilk defa Karadeniz kıyılarında yapılmış ve günümüze kadar pek çok çalışma ile denizlerdeki plastik kirliliğinin denizel canlı türlerindeki birikimi incelenmiştir. Çalışmalar sadece sediment ve deniz suyu ile sınırlı kalmamış, farklı balık, krustace ve omurgasız canlı türlerinde de araştırmalar gerçekleştirilmiştir. Şekil 1'de Türkiye'deki 4 denizde yapılan çalışmaların sayısal verileri yer almaktadır. Bu sonuçlara göre, Marmara denizi 27, Karadeniz 26, Akdeniz 17 ve Ege Denizi 11 çalışma ile denizel ortamdaki mikroplastik kirliliğinin güncel sonuçları verilmiştir. 2022-2024 yılları arası (15 araştırma makalesi) en yoğun çalışmaların yapıldığı dönemdir. Ancak 2025 yılında yapılan 8 çalışma ile bu araştırmaların çok daha fazla hız kazanacağını görmekteyiz. Türkiye denizlerinde gerçekleştirilen çalışmaların toplam sayısı 81'dir. Çalışmalar daha çok balık türleri ve deniz sedimanı üzerine yoğunlaşmıştır. 23'ü sediman, 18'i deniz suyu, 2'si çeşitli krustase türleri, 14'ü çeşitli bivalve-mollusk türleri, 25'i çeşitli balık türleri, 1 yunus, 1 deniz kestanesi, 1 deniz anemonu, 2 deniz atı ve 2 zooplankton türü üzerinde farklı araştırmalar yapılmıştır. Bu türlerdeki polimer birikimleri, çeşitleri boyutları ve kirlilik kaynakları incelenmiştir. Türkiye'de yapılan bu çalışmalardan 28 farklı polimer madde belirlendi. Bunlar, polipropilen (PP), polietilen (PE), polietilen tereftalat (PET), poliamid (PA) polivinil klorür (PVC) ve polistiren en yoğun belirlenen polimer türleri arasında yer almaktadır. Şekil olarak daha çok lif, parça ve köpük daha çok belirlenmiştir. Renklerde ise en baskın olanlar mavi, siyah şeffaf ve beyazdır. Kirlilik kaynakları ise Antropojenik, atık arıtım tesisleri, endüstri deşarj suları, evsel atıklar, belediye atıkları, tarımsal kaynaklar ve karasal girdiler olarak sıralanmıştır. İnsan kaynaklı kirliliğin etkisi; ağır metal, pestisit, petrol türevleri vb. konularda da çalışılmış pek çok farklı konularda da incelenmiştir. Ancak, mikroplastik Dünya genelinde de en güncel kirlilik konuları arasında birinci sırada yer almaktadır.

Bu derlemede, Türkiye'de yer alan 4 denizinden örneklenen çalışmaların verileri tablo halinde sunulmuştur. Çalışmaların gerçekleştiği bölgeden, örnek tipi, istasyon sayısı, partikül miktarı, plastik tipi, plastiklerin şekil renk ve boyutu ile kirlilik kaynakları ayrıntılı olarak verilmiştir. Bundan sonraki yapılacak çalışmalar için iyi bir kaynak oluşturacağı inancındayız.



Şekil 1. Yıllara göre Türkiye denizlerinde gerçekleştirilen mikroplastik çalışmalarının dağılımı.

Karadeniz'de gerçekleştirilen Mikroplastik çalışmaları

Referans	Bölge, Örnek Tipi ve İst. sayısı	Partikül miktarı	Plastik Tipi	Plastik şekli, rengi ve boyutu	Kirlilik kaynakları
Terzi vd. (2022)	Güney Karadeniz Sediment Yüzey suyu İst. sayısı :23	Sahil sedimentinde 64.06 ± 8.95 parça/kg, yüzey suyunda 18.68 ± 3.01parça/m^3	sediment (parça/kg) değeri yüksek olan maddeler %40.53 SAC (styrene acrylonitrile copolymer), % 38.75 PET (polyethylene terephthalate) ve %6.91 PE (polyethylene) Yüzey suyunda (parçaçık/m^3) PET (%57.26), PE (%13.52) ve PP (%11.24) (polypropylene)	Yoğun olarak lif ve parçalardan oluşuyordu Plastik boyutunun %70'inden fazlası < 2,5 mm	1368 şüpheli mikroplastik mikroplastik parçacıklarının yüksek bir yüzdesi polimerden oluşmaktadır (%94,19 plaj tortusundan ve %95,87 deniz suyundan). Karadeniz'in güneybatı kıyısı fazla sanayileşmiş ve nüfuslanmıştır. Tesisler, rüzgarlar ve akıntıların çalışma alanında mikroplastik dağılımının ana itici güçleri olduğu ifade edilmişir.
Akkan vd. (2023)	Güneydoğu Karadeniz Sediment İst. Sayısı:13	175 MP kg^{-1}	PE (%44,9), PET (%27,2) PP (%15,2)	parça (%51,5), lif (%30,8) > film	Mikroplastiklerin oluşumunda en önemli etkenin popülasyon yoğunluğu ve

				(%4,8) > köpük (%3,9) > pelet (%0,5) MP'lerin 104 µm - 4987 µm arasında değişmekte. ortalama uzunluğu 1753 µm'dir. %70'inden fazlası 2,5 mm uzunluktadır.	akarsuların deşarj noktaları olduğu, insan faaliyetleri ve nehir deşarj noktalarının diğer noktalara kıyasla daha kirli olduğu belirtilmiştir.
Şentürk vd. (2020)	Güney Karadeniz <u>Bivalve:</u> 5 tür (89 adet) *Donax trunculus, Chamelea gallina, Abra alba, Anadara inaequivalvis Pitar rudis* İst. Sayısı: 2	1.69-4mp.ind^{-1}	--	Lif, 0.15-4.56 mm, Mavi (%43), siyah (%32) ve yeşil (%7)	Çift kabuklu türlerinin MP kontaminasyonuna karşı hassas oldukları ve potansiyel biyoindikatör türler olarak kullanılabileceği ifade edilmiştir. Kirlilik etkenini daha çok karasak kaynaklı kirlilik oluşturmaktadır.
Senturk vd. (2023)	Güney Karadeniz *Syngnathus acus* (98 adet) denizatı Balıkçılardan toplanmış	1.38 mp fish^{-1}	PET, PE, PP	MP'ler çoğunlukla lif şeklindeydi (%89), siyah renkteydi (%52) ve 0,2- 1 mm (%52) ortalama 1.25±0.88 mm	--
Şentürk ve Aytan (2024)	Karadeniz Bivalve (2478 adet) Gastropod (230 adet) İst. Sayısı:14	Bivalve; 0-0.14 Gastropod; 0-0.006 mp.ind^{1}	--	Parça Bivalve; 22-27 Gastropoda; 26±3µm Siyah, mavi, kırmızı ve sarı renkler.	Habitat tahribatı, kirlilik, balıkçılık ve iklim değişikliği gibi önemli antropojenik baskılar altında olan Karadeniz kıyı biyoçeşitliliği için artan bir tehdit olduğunu ifade etmişlerdir.

Aytan vd. (2020)	Güney Karadeniz <u>Balık:</u> *Engraulis echrasicolus* 230 adet) <u>Zooplankton:</u> 2136 adet *Acartiura clausi* ve 2123 adet *Calanus euxinus* İst. Sayısı:12	0.002 parça/ <u>*A. clausi*</u> ve 0.004 parça/ <u>*C. euxinus*</u> <u>Hamsi</u> 0.25 ± 0.57 mp.ind^{1}	--	<u>*A. clausi*</u>: 0.104 - 0.153 mm Parça ve siyah, kırmızı. <u>*C. euxinus*</u>: 0.033 - 0.163 mm, Parça, kırmızı, siyah ve mavi renkler. <u>Hamside;</u> 1.55 ± 1.29 mm lif, siyah	Zooplankton ve ticari açıdan önemli bir tür olan Avrupa Hamsisi tarafından plastik yutulması incelenmiştir.
Atamanalp vd. (2021)	Karadeniz/ Sinop-İnceburun <u>Balık:</u> 2 tür (164 adet) *Alosa immaculata* Mullus barbatus Beyin, Solungaç, Kas ve Mide - bağırsak Balıkçılardan toplanmış	0.89MP fish^{-1}	PP (%18,8) PA (%15,0)	Balık türü gözetmeksizin MP karakterizasyonu çoğunlukla lifli (%51,0), siyah renkli (%49,0) ve 50-200 µm boyutunda (%55,0)	--
Köktürk dv. (2024)	Karadeniz/ Sinop-İnceburun <u>Balık:</u> *Scophthalmus maximus* (20 adet) Beyin, Karaciğer, Solungaç,Kas ve Mide - bağırsak Trol avcılığı	mide bağırsak 2,3 ± 1,6 solungaç 2,5 ± 1,5 MP/birey Kas 0,7 ± 0,2 MP/g dokudur.	% 35.5 Etilen propilen, % 29.0 Polikloropren, % 12.9 Poliamid (PA), % 9.7 idi Polipropilen (PP), % 6.5 Polivinil klorür (PVC), % 3.2 Polivinil alkol (PVA) %3.2 Polimetil penten (PMP)	siyah (%43-47), mavi (%30-35), sarı (%8-13), lifl, parça ve pelet MPS'nin çoğunluğu 50-200 µ	Otomotiv endüstrisinde yaygın olarak kullanılan ve yüksek su direncine sahip olan etilen propilen, bazı polimer türlerinde statik ve dinamik uygulamalarda çok iyi özelliklere sahip olması nedeniyle baskın MP türü olarak belirlenmiş, bunu polikloropren izlemiştir.
Aytan vd. (2022a)	Güney Karadeniz <u>Balık:</u> 7 tür (650	incelenen tüm bireylerin %29'u)	polipropilen (%29,8), polyester (%17,5),	En yaygın plastik türleri lifler	--

	adet) *E.encrasicolus, Trachurus mediterraneus, Sarda sarda, B. belone, Pomatus saltatrix, M. merlangus Mullus barbatus.* Mide-bağırsak Trol avcılığı	toplam 352 plastik parçacık çıkarıldı. Balık başına düşen ortalama plastik parçacık sayısı 0,81±1,42 par.ind^{-1}	akrilik (%15,8), polietilen (%14) polistiren (%1,8) polimerlerin %21,1'i selüloziktir	(%68,5), ardından filmler (%19), parçalar (%11,9), köpükler (%0,3) ve mikrobon cuklar (%0,3) olmuştur. En yaygın plastik rengi siyah (%39,3), ardından mavi (%19,5) ve şeffaf (%18,1) olmuştur. Plastiklerin uzunlukları 0,05 ila 26,5 mm arasında değişmiş olup, ortalama 1,84±2,80 mm'dir. Plastiklerin %93,2'si mikroplastik, %6,5'i mezoplastik ve %0,3'ü makroplastiktir	
Aytan vd. (2016)	Güneydoğu Karadeniz Zooplanktn İst. Sayısı:12	0,2 × 10 3 $^{-3}$, 3 × 10 3^{-3} par	--	Nötonik örneklerin %92'sinde mikroplastik (<5 mm) Birincil tipler liflerdi	Karadeniz'de ilk kez nötronik mikroplastik değerleri raporlandı.
Aytan vd. (2022b)	Güneydoğu Karadeniz <u>Zooplankton</u> *C. euxinus* *A. clausi* İst. Sayısı:3	Ortalama mikroplastik yutma miktarı *C. euxinus* ve *A. clausi* için sırasıyla 0,024 ve	polietilen tereftalat (PET), %20,9 poliamid (PA) veya naylon %10,5 polipropilen	Lif Film parçalar 0,104 ile 4,97 mm 1-2 mm Mavi renk baskın	Su sütunundaki en yaygın MP'ler lifler olup olası kökenleri belediye atık su bertarafı olarak belirtilmiştir.

		0,008 mp·ind $^{-1}$ 0,12–7,63 2,04 ± 1,05 mp·m $^{-3}$	(PP) %7 poliakrilonitril (PAN) veya akrilik, %7 polietilen (PE) %5,8		
Öztekin vd. (2024)	Karadeniz/ Sinop Hamsilos Körfezi İst. Sayısı:1	3194 adet mikroplastik parçacığı 1.74 ± 0.80–21.07 ± 3.84 parça/m^3	PET (%47), PE (%34), HDPE (%10), PVC (%7) PS (%2)	lif (%73,92), boyut sınıfına göre 1–2 mm (%28,35) ve renge göre mavi (%37,98)	Şehir balıkçılık, tarım ve turizm dahil olmak üzere kıyı çevresini etkileyebilecek çeşitli faaliyetlere ev sahipliği yapmaktadır. Sinop kıyılarında olası çöp kaynakları olarak uygunsuz atık ve kanalizasyon yönetimi, nehir akışı, turizm, balıkçılık, su ürünleri yetiştiriciliği ve nakliye ile öncelikle kara kaynaklı çöp maddeleri gelmektedir. Su sütununda en yaygın mikroplastik şekli atık su deşarjından kaynaklanan lifler olarak belirtilmiştir.
Öztekin ve Bat (2017)	Karadeniz/ Sinop Sarıkum Lagünü Deniz suyu İst. Sayısı:1	2.67±2.33 parça m^{-3}	--	siyah, beyaz ve mavi renk baskın En yaygın malzeme türü; gemi boyaları (Deniz yüzeyi:% 55.45; su sütunu:% 54.21), lifler, sert plastik parçalar ve naylon çorap.	Çalışma sonuçları deniz ortamının denizcilik faaliyetleri sonucunda yoğun miktarda kirleticiye maruz kaldığını göstermiştir. Özellikle sonbaharda, mikro çöp kaynağı olarak balıkçılık faaliyetleri dikkat çekmektedir. polistiren kutu kalıntıları ve balıkçılıkta kullanılan polistiren bazlı köpük kutular başta yer almaktadır. Balıkçılık faaliyetlerinden kaynaklanan bir diğer kirletici ise yakıt kirliliğidir.

Bayık ve Aydemir (2023)	Karadeniz Batı Anadolu Zonguldak Balıkçı barınağı Deniz suyu İst. Sayısı: 1	Ortalama 3400±1400 adet/m3 ve 1200 ila 5860 adet/m3 aralığındadır.	--	Mikroplastiklerin (%60) yaygın boyutu <50 µm'dir. Baskın renk mavi, siyah, yeşil, kırmızı, beyaz ve gri.	--
Eryaşar vd. (2022)	Karadeniz <u>Balık:</u> 3 tür (371 adet) *E. encrasicolus*, *M. merlangus* *M. barbatus* Mide - bağırdak İst. Sayısı:9	*E. encrasicolus, M. merlangus M. barbatus* (MP bolluğu balık başına) 0,15 ± 0,04, 0,28 ± 0,06 ve 0,40 ± 0,07	PP (%35) > PE (%23) > PET (%15) > PA (%12) > PS (%10) > PAN (%3) > PVC (%1) = SAC (%1).	MP'lerin boyutu 118 µm ile 4854 µm lif (%49) formunda, ardından parça (%42) > pelet (%3) > film (%1)	Kanalizasyon ve nehir akışından, Karadeniz'deki yoğun balıkçılık faaliyetleri ve olta takımlarının ve iplerinin atılması önemli lif kaynaklarıdır.
Eryaşar vd. (2021)	Güneydoğu Karadeniz Deniz suyu İst. Sayısı:3	MP'nin bolluğu 0,181- 0,94 m^{-3}	polietilen (%44,9) polietilen tereftalat (%25,3)	parçacık (%56,3) MP boyutları 118 - 4998 µm ve %50'si 2000 µm'den küçüktü.	Ancak çalışma alanının balıkçı limanlarına yakınlığı göz önüne alındığında, bölgedeki yüksek miktardaki köpüğün kaynağı yoğun spor balıkçılığı veya av balıkçılığı ile nehir deşarjlarından kaynaklanmaktadır.
Gedik ve Gözler (2022)	Güneybatı Karadeniz <u>Bivalve:</u> *Chamelea gallina* Sediment İst. Sayısı:15	Sedimentler de 28-684 MP kg^{-1} arasında değişirken , C. *gallina*'da bireysel MP'ler 0,22–2,17 MP kg^{-1}	PET, PP ve PE polietilen tereftalat (%34,2-35,1), polietilen (%28-31,1) ve polipropilen (%18,9-21)	MP'lerin en baskın şekli ise lifttir (sedimende %56,5 ve *C. gallina* için 68,9). Mikroplastik boyutları 73-4987 µm arasında değişiyordu. Sedimentlerdeki ve *C.*	Kirlilik kaynağı belediye katı atık depolama alanları ve bölgede üretilen kentsel ve endüstriyel atıkların herhangi bir işleme tabi tutulmadan doğrudan deniz ortamına deşarj edilmesi olarak belirtilmiştir.

				gallina'daki MP'lerin sırasıyla %47'si ve %65'i <1000 µm boyutundaydı.	
Gedik vd. (2023)	Güneydoğu Karadeniz Balık: *E. encrasicolus* (360 adet) Mide-bağırsak Balıkçılardan toplanmış	2 MP olmak üzere 0 ind. $^{-1}$ ile 0,43 ind. $^{-1}$	PP (%42,9) PE (%22,4)	lifler (%51,0), fragmanlar (%32,7), filmler (%12,2) köpük (%4,1). Renkler; siyah (%26,5) beyaz (%24,5), kırmızı (%22,5), şeffaf (%10,2), yeşil (%8,2), mavi (%6,1) ve sarı (%2,0) Boyut: 96-4600 µm arasında değişmekte olup ortalama 735,32 ± 836,62 µm'dir.	Karasal kaynaklı girdilerin suya geçişi olarak ifade edilmiştir.
Gedik ve Eryaşar (2020)	Karadeniz, Marmara Denizi ve Ege Deniz Bivalve: *Mytilus galloprovincialis* (342 adet) İst. Sayısı: 23	Ortalama MP sayısı 0,23 adet/g (yaş ağ.) (0,69 adet/midye)	PET (%32,9) PP (%28,4) PE (%19,4)	parçalar (%67,6) > lifler (%28,4) > filmler (%4,05). MP'lerin baskın boyutu 0,5 mm'den küçük (%26,58) Ortalama MP uzunluğu 1,66 ± 1,45 mm (0,07-4,94 mm) .	--
Mutlu vd.	Karadeniz	0.22±0.14	PE (52%) >	elyaf	--

(2022)	<u>Balık:</u> *Trachurus mediterraneus* (121 adet) Mide-bağırsak İst. Sayısı:9	MP	PP (30%) > PET (11%) > PAN (7%)	(%60) parça 5 ist. (%27) film 2 ist. (%7) Boyut:102 -2477µm	
Onay vd. (2023a)	Karadeniz <u>Balık:</u> *Hippocampus guttulatus* Deniz atı (90 adet) Mide-bağırsak Balıkçılardan toplanmış	GITs sampled during both 2012 and 2022 contain 102 and 135 MP ürün.	PVS (%80)> PVPP (%8)> PE (%4) = PP (%4) = PCT (%4) ve PVS (%53)> PE (%19)> PET (%11)> PVPP (%9)> EVA (%4)> PP (%2) = PCT (%2)	lif, parçacık ve köpük beyaz (%52) siyah (%28) Boyut: 2021 yılı için; 215-5087 µm, 2022 yılı için 126–9957 µm	Bölgedeki MP kirliliğinin dar kıta sahanlığına bağlı kentsel sulardan (belediye atık sularında özellikle çamaşır suları) ve balıkçılık faaliyetleri sırasında kullanılan halat ve ağlardan kaynaklandığı ifade edilmiştir.
Onay vd. (2023b)	Güneydoğu Karadeniz <u>Balık:</u> *M. barbatus* (120 adet) Mide-bağırsak Trol avcılığı	yıllık toplam 335 MP	PVA, PE, PAN, PVC, PET, EVA, PVDF, PCT, PP	Lif ve parçacık, MP uzunlukları 339-46.706 µm Baskın renk mavi, beyaz (%50)	Lif MP'lerinin kaynağı; -Yoğun balıkçılık faaliyetlerinden kaynaklı balıkçı ipleri, ağlar gibi atıklar, -Yüzme ve rekreasyon gibi turistik amaçlardan kaynaklanan antropojenik etkenler - Belediye suyu tarafından yapılan deşarjlar.
Tepe vd. (2024)	Güneydoğu Karadeniz Giresun <u>Balık:</u> 4 tür (40 adet) *E. encrasicolus* *T.trachurus* *M. barbatus* *M. merlangus* Mide-bağırsak Balıkçılardan toplanmış	1.7 ± 0.18 MP balık^{-1}	PP (%56) PA (%25) PES (%19)	Lif, Parça ve Pelet siyah %41 mavi %24 kırmızı yeşil % MP'ler 0,026–5 mm	--
Fıçıcılar vd. (2025)	Orta Karadeniz <u>Balık:</u> 9 tür (270 adet)	111 MP tanımlanmış	PE (%40), PET (%25) PP (%15) PS (%5)	lif, film, fragman, köpük 9 farklı plastik	--

	E. encrasicolus, M.merlangus, M.barbatus, T. mediterraneus, Sarda sarda, Spicara flexuosa, Belone svetovidovi, Pomatomus saltatrix Neogobius melanostomus Mide-bağırsak İst. Sayısı:3			rengi bulundu; siyah (%66,13), mavi (%19,5), şeffaf(%18,1), kırmızı (%9,2), turuncu (%4,6), yeşil (%3,4), beyaz (%2,9), sarı (%1,1), gri (%0,9), pembe (%0,9) mor (%0,3) Boyut; 0.10-3.5mm, ortalama boyut 0.2–1mm (%38).	
Kılıç ve Uncumusaoğlu (2024)	Karadeniz/ Ordu Sediment Deniz suyu İst. Sayısı:6	sediman örneklerinde 291.11 öğe kg^{-1} MPs ve su örneklerinde 0.263 öğe L^{-1} MPs . Toplam 420 MP parça.	polietilen (%56) polipropilen (%19), polistiren (%15), polivinil asetat (%7) polilen tereftelat (%3)	Lif ve film tipi baskın. Mavi, şeffaf renkler, MP boyutu 0-50µm (%50,71) aralığında ve tespit edilen MP'lerin 800 µm'den büyük değildir.	Örnekleme bölgelerindeki kirlilik kaynakları; Kentsel atıksu arıtma tesisi, akarsu deşarj noktası, nüfus yoğunluğunun en yüksek olduğu bölge, liman ve sanayi tesislerine yakınlık olarak ifade edilmişyit.
Şener vd. (2019)	Karadeniz/ İstanbul Sediment İst. Sayısı:6	20.7 parça/kg (kuru ağ.)	--	1-5 mm	--

Akdeniz'de gerçekleştirilen Mikroplastik çalışmaları

Referans	Bölge, Örnek Tipi ve İst. sayısı	Partikül miktarı	Plastik Tipi	Plastik şekli, rengi ve boyutu	Kirlilik kaynakları
Gündoğdu vd. (2017a)	Mersin Körfezi/Kuzeydoğu Levanten kıyıları Yüzey suyu İst. Sayısı: 7	0,376 adet/m^2	--	Lif (%60,1) En baskın renk şeffaf Şekil: Silindirik, Uzun, Düz, Düzensiz ve Küresel Boyut: 0-5 mm	--
Gündoğdu vd. (2017b)	Mersin Körfezi/ Kuzeydoğu Levanten kıyıları Tolanan atık ve üzerinde yaşayan biota İst. Sayısı:4	2670 adet/km2 plastik , 86,3 kg/ km2 ağırlıkta plastik	PE, PP, EPC, PET, NY-6, PS, SAC, Poli-E PVC	--	--
Gündoğdu (2017)	İskenderun Körfezi Deniz suyu İst. Sayısı:14	1067 (item/m^2)	--	MPs partikül sayısı 2729 parçacık (%29) Parçacık (%64,6) En baskın renkler şeffaf, siyah, beyaz. Boyut: 0,1-0,3 mm	--
Gündoğdu vd. (2018)	Mersin Körfezi Deniz suyu İst. Sayısı:4	1197 MP ve 22.785 MP	PE (%55,2), PP (%26,9), SAAC (%4,7), PS (%4)	Lifler, Filmler, Köpükler, Parçalar ve Peletler Boyut: 0,1 mm ve 0,3-0,5 mm	Deniz ekosistemlerindeki MP'lerin en önemli kaynakları nehirler, deniz trafiği ve balıkçılık faaliyetleridir. Plastiklerin deniz ekosistemlerindeki dağılımı birçok hidrografik faktör tarafından kontrol edilir; bunların en önemlileri yüzey akıntıları, dalga hareketleri ve rüzgarlardır. Şiddetli yağışları takip eden sellerin yanı sıra diğer faktörlerin de plastik konsantrasyonlarının artmasına katkıda bulunabileceği ifade edilmiştir.
Gündoğdu ve Çevik (2019)	İskenderun Körfezi kuzey levantin	Ortalama 12,2 ± 3,5 adet m^{-2} ve 12,3 ± 3,5	--	(%59,4) 2,5 cm'den küçüktü.	etkisiz atık yönetimi , aşırı kentleşme ve sanayileşme, hakim

	kıyıları Kıyı Sedimenti İst. Sayısı:13	gr m $^{-2}$		lastikler için en sık görülen renkler beyaz (%24,59), şeffaf (%15,95) ve mavi (%13,79) idi	akıntılar nedeniyle Doğu Akdeniz çevresindeki diğer ülkelerden gelen atıklar ve tarımsal faaliyetler sonucu tarlaya terk edilen tarımsal plastikler olabilir. yerel yönetimlerin plaj temizleme çalışmaları yetersiz ve etkisizdir ve plajlarda makro mezo ve mikro plastik çöplerin birikmesini artırır.
Gedik vd. (2022)	Doğu Akdeniz'in Türkiye kıyıları Sediment İst. Sayısı:47 Yüzey suyu İst. Sayısı:29	Sediment 2452 MP 118 ± 97 kg^{-1} 1688 ± 746 kg^{-1} Yüzey suyu 3856 MP	Sediment PE (%59,2) PP (%22,8) PET (%13,2) AC (%4,9) Yüzey suyu PE (%64,8) PP (%21,3) PET (%10,6) AC (%3,3)	Sediment parça (%57,6) lif (%27,0) film (%15,3) küre (%0,1) Boyut: 102 -4990 µm Yüzey suyu Parça (%70,5) lif (%20,3) film (%9,2) Boyut: 73,25 -4984 µm	Bölgedeki tarımsal faaliyetlerde PE levhaların yoğun kullanımı, kıyı sularının kentsel deşarjlara yoğun şekilde maruz kalması sonucu ikinci baskın lif türü olmuş, bununda ana kaynağı deşarj sularıyla ortama giren sentetik kumaşların yıkanmasıdır. Ayrıca, balıkçılık ve su ürünleri yetiştiriciliği faaliyetlerinde kullanılan ağlar da başka bir lif kaynağı oluşturmaktadır.
Çevik ve Gündoğdu (2018)	İskenderun Körfezi/ Yumurtalık Körfezi <u>Mollusk:</u> Bivalve (30 adet) *Spondylus spinosus* İst. Sayısı:1	1.8 - 2.6 items per individual 1.8-2.1 particles per g	--	Lif, parça ve film, Boyut: 0,01-5,2 mm.	--
Gündoğdu vd.(2020)	Mersin Körfezi <u>Balık:</u> 4 tür (57 adet) *L. mormyrus* *C. saliens* *M. barbatus barbatus* *T. mediterraneus* Mide-bağırsak Balıkçılardan toplanmış	1.8ind.$^{-1}$	PE, PP, PET, PES	Lif (%24,9), Parça (%75,1)	--
Güven vd. (2017)	<u>Balık:</u> 28 tür 14 familya (1337	2.36 MP (Pieces.ind^{-1}) 1.8±0.9 items	HIPPS PP PA	Lifler (%70) sert plastik (%20,8)	--

	adet) *Dentex dentex* *Caranx crysos* *Dentex gibbosus* *Diplodus annularis* *Lagocephalus spadiceus* *Lithognathus mormyrus* *Liza aurata* *Mullus barbatus* *Mullus surmuletus* *Nemipterus randalli* *Pagellus erythrinus* *Pagrus pagrus* *Pelates quadrilineatus* *Pomadasys incisus* *Sardina pilchardus* *Saurida undosquamis* *Sciaena umbraScomber japonicus* *Serranus cabrilla* *Siganus luridus* *Sparus aurata* *Trachurus Mediterraneus* *Trigla lucerna* *Umbrina cirrosa* *Upeneus poriUpeneus moluccensis* Mide-bağırsak İst. Sayısı:18	/individual km^2 başına 16- 339 3.75items/individual	LDPE	naylon (%2,7), kauçuk (%0,8), çeşitli plastik (%5,5) Baskın renk: mavi, şeffaf Boyut: (%94) 0,1 -2,5 mm	

Kılıç ve Yücel (2022)	Kuzeydoğu Akdeniz Balık: 4 tür (153 adet) *M.barbatus* *M.surmuletus* *M.cephalus* *S. undosquamis* Solungaç Mide-bağırsak Balıkçılardan toplanmış	*M. barbatus, M. surmuletus, S. undosquamis ve M. cephalus'un* mide-bağırsak: 3.22 MPs fish^{-1}, 7.56 MPs fish^{-1}, 3.57 MPs fish^{-1} ve 26.15 MPs fish^{-1} M. barbatus, M. surmuletus, S. undosquamis ve M. cephalus'un solungaç: 3.54 MPs fish^{-1}, 4.65 MPs fish^{-1}, 2.70 MPs fish^{-1} ve 3.85 MPs fish^{-1}	PE (%34) PET PA	lifler (%95) parçacık(%4) En baskın renkti mavi (%53), beyaz/şeffaf (%12), kırmızı (%11), yeşil (%4), kahverengi (%2), turuncu (<%1) Boyut: 1.33 ± 1.31 mm	PE'nin başlıca kaynaklarının plastik poşetler ve şişeler olduğu bildirildi.
Kılıç (2022a)	Mersin/ İskenderun Körfezi Balık: 3 tür (73 adet) *Oncorhynchus mykiss* *Sparus aurata* *Dicentrarchus labrax* Mide-bağırsak Balıkçılardan toplanmış	Gökkuşağı alabalığı, çipura ve Avrupa levreğinin ortalama MP bolluğu sırasıyla 1,2 ± 1,3 MP balık^{-1} , 0,8 ± 1,1 MP balık^{-1} 0,95 ± 1,1 MP balık^{-1} 4.22MPper fish	polyester (%20), PA (%10), PE (%25)	Lif (%80) Renk: siyah (%61), kırmızı (%5), mavi (%27), şeffaf (%2) yeşil (%6) Boyut: 1,4 ± 1,3 mm	Yetiştirilen gökkuşağı alabalığı, çipura ve Avrupa levreği türlerinde mikroplastik yutulmasını inceleyen ilk çalışma. Sadece doğal değil aynı zamanda balıkçılık çiftlikleri gibi insan yapımı ortamlarda da ortaya çıkan bir sorun olduğunu göstermiştir. Kanalizasyon çıkışlarının, atık su arıtma tesislerinin ve balıkçılık endüstrisinin mikroplastik kontaminasyonunun ana kaynaklarıdır
Kılıç (2022b)	İskenderun Körfezi Balık: *Chelon ramada* (30 adet) Mide-bağırsak Solungaç Balıkçılardan toplanmış	158 MPs Solungaç: 1.9±1.8 parça/birey Mide-bağırsak: 3.4±2.1 parça/birey	PET, PES, PA PP	Lif (%79), parçalar (%16), film (%4) pelet (%2) Renk: siyah ve şeffaf Boyut: 1251±1602 µm	Antropojenik kaynaklı
Kılıç ve Uğurlu (2024)	İskenderun Körfezi Echinoderm: *Diadema Setosum* (19	Mide-bağırsak: 3.0 MPs±3.1 MPs per/birey 0.9±1.0 MPs	PE (%50) PP (%50)	Lif (%45) Parça (%44) peletler (%11) Renkler:	Bunlar, balık ağlarının üretiminde kullanılan ana polimerlerdir; bu nedenle, bu sonuç çalışma alanındaki

	adet) Mide-bağırsak Gonad Balıkçı barınak noktalarından toplanmış	per/ g yaş ağ. Gonad: 0.3±0.6 MPs per/birey 0.08±0.2 MPs per/ g yaş ağ.		siyah, mavi, yeşil, kırmızı renk ve renksiz(beyaz ve şeffaf)	antropojenik etkiyi göstermektedir.
Koraltan vd. (2022)	Balık: 17 tür (2222 adet) *Boops boops* *Dentex macrophthalmus* *Dentex maroccanus* *Lepidotrigla cavillone* *Mullus barbatus* *Mullus surmuletus* *Nemipterus randalli* *Saurida lessepsianus* *Trigla lucerna* *Upeneus moluccensis* *Upeneus pori* *Oblada melanura* *Pagellus erythrinus* *Etrumeus golanii* *Sardina pilchardus* *Scomber scombrus* *Trachurus mediterraneus* Mide-bağırsak Trol avcılığı	birey başına ortalama 1,3 MP	PP (%85) PE PES PVA	lif (%90,1) film (%6,5), parçacık (%3,0), pelet (%0,2) kauçuk (%0,2) Renk: siyah (%46,9) ve mavi (%29,4). Boyut: 1,26 ± 1,38 mm	--
Tümerkan vd. (2024)	Mersin Körfezi/Akdeniz Kinidliler: *Actinia equina* (Deniz anemonu) Sediment Su İst. Sayısı: 3	*A. equina* 19,3 gramda ortalama 1,95 mikroplastik parçacık. Sedimanlarda toplam MP sayısı, İstasyon 3'te daha yüksekti (135 MP kg-1), İstasyon 2'yi (109 MP kg-1) ve İstasyon 1'i (59 MP kg-1) Deniz	*A. equina* PE, PP, PET Sediment; PE, PP, PET Deniz suyunda; PE	*A. equina:* Lif en baskın sonra parça ve film, pelet. Sediment: Lifti, elyaf, parçalara ek olarak, film. Yüzey deniz suyu örneklerinde parça ve lif baskındı. Renk: şeffaf tüm örneklerde baskın renk.	Turizm, balıkçılık, evsel faaliyetler gibi antropojenik etkilerle ilişkili olduğu ifade edilmiştir.

		Suyunda 1 ist. 389 parça, 2.ist. 1070 ve 3. İst 1680 parça		Mavi deniz suyunda ve anemonda, sedimanda ise siyah ikinci baskın. MP'lerin boyut: 0,023 - 4,83 mm	
Yücel vd. (2022)	İskenderun Körfezi Memeli: *Grampus griseus* (yunus balığı) Mide-bağırsak Arsuz-Uluçınar kıyılarında karaya vuran	A total of 484 MPs partikül	--	Lif (%96). Renk: beyaz, siyah, mavi, yeşil ve kırmızı Boyut: 1.3±1.6 mm.	
Yücel (2023)	Kuzeydoğu Akdeniz/ Mersin ve Samandağ Krustase: *Parapenaeus longirostris* (karides/46 adet) İst. Ssyısı: 2	Toplam 864 MP ortalama MP sayısı 18,8	PE PET	Lif siyah (%46), mavi (%21), kırmızı (%13) Boyut: 1000-2500 µm Samandağ; 9.7 ± 24.4 MPs ind^{-1}. lif (100%), siyah (46%), boyut, 1–2.5 mm ve PE.	Bu çalışma, kuzeydoğu Akdeniz'deki *P. longirostris*'te mikroplastik oluşumunu ve lif düğümlerini değerlendiren ilk rapordur. Yüksek miktarda deniz çöpüve antropojenik baskıların özellikle Samandağ bölgesinde aşırı mkroplastik kirliliği sergilemiştir.

Marmara Denizi’nde gerçekleştirilen Mikroplastik çalışmaları

Referans	Bölge, Örnek Tipi ve İst. sayısı	Partikül miktar	Plastik Tipi	Plastik şekli, rengi ve boyutu	Kirlilik kaynakları
Doğruyol vd. (2019)	Haliç, İstanbul Sediment İst. Sayısı: 7	11.1258 g/kg	--	> 5 mm (198 parçacık), 1-2 mm (118 partikül) Film	Evsel ve endüstriyel, deşarj, aşırı kirlilik ve turizm
Baysal vd. (2020)	Marmara Denizi Sediment İst. Sayısı:14	0.3-85.6 g/kg 13–5100 partikül/kg	ABS, EVA, PS, PP, PC, PU, PE, PVC, PETE, Latex	parça>lif>Film siyah	Gemi trafiği, antropojenik, endüstriyel faaliyetler
Erkan vd. (2021b)	Marmara Denizi ve Boğazlar Sediment İst. Sayısı:43	1957.37±4079.96 MPs/kg kuru ağ.	HDPE	Filament ve parça Renk: Mavi ve beyaz Boyut: 1-5 mm boyut	Turizm ve sanayi aktiviteleri, deniz ulaşım, tarım, belediye, nehir ve akarsu

				>300 µm	
Olguner vd. (2023)	İstanbul kıyıları Sediment İst. Sayısı:15	144-700 MP kg $^{-1}$ 326.62 particles/kg	PPS	Parça, lif 2 mm (%81.75)	Evsel atıklar, denizcilik, balıkçılık aktiviteleri, antropojenik kirlilik
Belivermiş vd. (2021)	Haliç, İstanbul Sediment İst. Sayısı: 10 derin nokta	700-4100 733 ± 3000MP (MP kg^{-1}) 1960 parça kg^{-1}	--	Parça, lif 100-400µm	İnsan aktiviteleri ve balıkçılık faaliyetleri
Erkan vd. (2023)	İstanbul kıyıları Sediment İst. Sayısı:43	7000 ± 10.400 parçacık kg^{-1} kuru ağ. 4337.5 parça kg^{-1}	PE, PP, neopren hortum kılıfı	Parça, lif ve film 0.3-1 ve 1-5 mm Mavi-beyaz >1000 µm	Tekstil, plastik üretimi ve deri tabaklama gibi endüstriyel faaliyetler, yoğun insan nüfusuna sahip marinalar ve deniz taşımacılığı.
Yücedağ vd. (2024)	Gemlik Körfezi Sediment İst. Sayısı:15	3333.3-9733.3 MPS/kg	PP, PVC, PPS	Fiber	Gemlik Körfezi'ndeki liman faaliyetleri, nehir deşarjları.
Mutlu vd. (2025)	Gulf of Bandırma Sediment İst. Sayısı:20	195-226 MPs/kg	PET	0.5-0.1, fiber, mavi ve siyah	--
Tuncer vd. (2018)	Marmara Denizi Yüzey suyu İst. Sayısı:18	1,263 birim/m²	--	Fil Parça, Lif, Granul Beyaz, mavi >1- <50 mm	Temel nedeni, belediyelerin, alt akıntının taşıyıcı olarak kullanılabileceğini varsayarak, gerekli herhangi bir arıtma işlemi yapmadan derin deniz deşarjlarını kullanan atık bertarafı.
Acar vd. (2022)	*Callinectes sapidus* (45 adet)	15 bireyde 46 parça bulunmuş	--	Siyah mavi	Kulanılan olta malzemelerinden olduğu ifade edilmiş.
İşlek vd. (2023)	Deniz suyu ve sediment İst. Sayısı:5	MP bolluğu 2922.32±517.35 MP/kg	--	Lif (%59), Parçacık (%14) Film (%23) Mikroboncuk (%4) Renkler: %42'si siyah; %23'ü şeffaf; %15'i mavi; %8'i kırmızı ve %12'si diğer Renk. MP boyutu:1-100 µm (%50)	MP kaynağı, tekstil sanayi kuruluşlarının kontrollü/kontrolsüz deşarjı ve balıkçılık faaliyetlerinden ileri gelen ağ ve olta takımı parçaları.
Sönmez vd. (2023)	Kuzey Marmara Denizi Deniz suyu İst. Sayısı:9	146.63 parça/L	EVA (%22,2) PE	Lif (%64,07) Baskın renk: şeffaf, (%9,09-44,97) mavi (%31,97) siyah (%27,78) Boyut: 100-249µm	Evsel atık su deşarjı da dahil olmak üzere antropojenik faktörler kirliliğin ana nedeni olarak açıklanmış.

Çullu vd. (2021)	Küçükçekmece Lagünü Yüzey suyu İst. Sayısı:10	47.62 ± 35.14 parçacık L^{-1} 41.46 ± 34.36 parçacık L^{-1}	PE	Lif, line ve film Baskın renkler: mavi, kırmızı ve yeşil Boyut: >50 µm	Atık su arıtım tesislerinden gelen sulardaki parçalardan çok etkilendiği ifade edilmiş. Yine balıkçılık ekipmanlarının parçalanma ürünlerini, örneğin ipleri ve ağları, plastik ambalaj malzemelerini ve yiyecek servis ürünlerini (plastik çatal, plastik kaşık, plastik kürdan ambalajı, hijyenik mendil ambalajı) de içerdiği belirtilmiş.
Erkan vd. (2021a)	Marmara Denizi Yüzey suyu İst. Sayısı:5	276.1857 partikül/km^2 3497.02 partikül/km^2	--	Parça, film, köpük ve iplik Baskın renk beyaz Boyut: 0,3-1-1-5 mm.	En yüksek MP bolluğu yoğun deniz taşımacılığı faaliyetlerinin olduğu iskele istasyonlarında bulunmuş. Çevredeki endüstriyel ve antropojenik faaliyetlere bağlı yoğun bir gemi hareketi bu etkiyi arttırmakta.
Gürkan ve Yüksek (2022)	Türk Boğazlar Sistemi Yüzey suyu (SW) Su kolonu (WC) İst. Sayısı:6	WC (4.12-34.90 items/m^3 SW (0.17-2.52 items/m3)	--	Lif (%76,80) Parça Boya partikülleri Renkler: Siyah ve mavi Boyut:0,3- 2,0 mm	Tarım ve balıkçılık faaliyetleri ve yaz aylarında turizm, körfezin ekosistemini etkileyen insan aktiflerinden bazılarıdır. Ayrıca, körfez çevresinde tarımsal faaliyetler yaygındır.
Gedik ve Eryaşar (2020)	Türkiye kıyıları Bivalv: *M.galloprovincialis* İst. Sayısı:4	0.4 MPs/kg	PET	Parçacık Boyut:1660±1450	--
Gedik vd. (2022)	Marmara Denizi Bivalv: *M. galloprovincialis* İst. Sayısı:20	2.06 MPs/kg	PET (%66,38).	Lif (%81,16) Boyut:100-4990 mm	Deşarja bağlı kirlilik tehdidi.
Tuçelli ve Erkan (2024)	Marmara Denizi Bivalv: *M.galloprovincialis* İst. Sayısı:6	1.33-8.45 MP/g	EPDM, EPR	Lif, siyah ve mavi, boyut: 0.1-0.5mm	Antropojenik faaliyetler.
Balcıoğlu İlhan (2025a)	Marmara Denizi Bivalv: *M. galloprovincialis* (322 adet) İst. Sayısı:18	0.88 to 6.82 parça/$birey^{-1}$ 0.84 to 6.7 parça g^{-1} yaş ağ.	PE (%44) PET, PP, ABS, PVC, PS	Lif (%61,08), Mavi (%57,87) ve Boyut : <0,5 mm (%62,55)	İnsan kaynaklı aktiviteler, akıntı sistemleri ve derelerin boşaltım noktası.
Balcıoğlu İlhan (2025b)	Marmara Denizi Sediment	199 – 1286 parça kg^{-1}	PE (% 47.2), PTE(%16.7)	lif (%35) parçalar (%27) Mavi (% 35.1),	İnsan kaynaklı baskılara ek olarak, substrat bileşimi ve hareketliliği, kıyı

	İst. Sayısı:21		, PP (%6.7), PVC(%13.8), ABS (%5.6).	siyah (%25.8) ve kırmızı (%24) . MP'lerin baskın boyut sınıfı <0,5 mm	jeomorfolojik özellikleri, nehir yakınlığı, hidrodinamik rejimler (örneğin, su akıntıları) ve hakim dalga ve rüzgar koşulları gibi bir dizi çevresel faktör, MP'lerin mekansal dağılımını şekillendirmede ve potansiyel kaynaklarındaki değişkenliği yönlendirmede kritik bir rol oynamaktadır.
Yibar vd. (2024)	Marmara Denizi <u>Bivalv:</u> *Mytilus* spp. (160 adet) İst. Sayısı:10	İst 5. %28.02 İst 2. %22.58 MP	--	Parça (% 26.1) Lif (%14.5), çizgi tipi (%6.3), pelet tipi (%2.7) Renk: siyah (%38.51)	Pandemi sonrası MP kirliliğinin neredeyse yüz kat arttığını ve önceki araştırmalara göre daha sınırlı bir coğrafi alanda önemli ölçüde daha yüksek bir varlık gösterdiğini ifade etmişlerdir. MP kirliliğinin kaynakları ise; kentsel akış, plastik atıklar ve endüstriyel deşarjlar.
Mutlu vd. (2025)	Bandırma Körfezi <u>Bivalv:</u> (180 adet) *Ostrea edulis* *Mytilus galloprovincialis* *Rapana Venosa* İst. Sayısı:20	2.6 ± 0.9	PET	Lif Mavi, siyah 0.1-5mm	--
Gündoğdu vd. (2020)	Marmara Denizi <u>Balık:</u> 5 tür (103 adet) L. mormyrus *C. saliens* *M. barbatus barbatus* *M. surmuletus* *T. mediterraneus* Mide-bağırsak Balıkçılardan toplanmış	1.9 MP(parça. birey^{-1})	PP, PE, PET, PES	Lif (%59.2), Parça (%40.8)	--
Mutlu vd. (2025)	Marmara Denizi/ Bandırma Körfezi <u>Balık:</u> 2 tür (112 adet)	2.13-3.54 MPs/kg	PET	Lif Mavi, siyah 0.1-5 mm	Arıtma tesislerinin etkisi, sentetik tekstillerin deşarj edilmesi ve balıkçılık araçlarının bozularak parçalanması sonucu oluştuğu belirtilmiştir.

	Mugil cephalus Pomatomus Saltatrix İst. Sayısı:20				
Aytan vd. (2023)	Marmara Denizi <u>Balık:</u> 13 tür (374 adet) *Trachurus mediterraneus, Chelon auratus, Merlangius merlangus, Mullus barbatus, Symphodus cinereus, Gobius niger, Chelidonichthys lastoviza, Chelidonichthys lucerna, Trachinus draco, Scorpaena porcus, Scorpaena porcus, Pegusa lascaris, Platichthys flesus.* Mide-bağırsak İst. Sayısı:1	1,14 ± 1,03 MP. balık $^{-1}$ 1,77 ± 0,95 MP	PET	Lifler (%74), filmler (%18) parçalar (%7), Renk: mavi (%62) Boyut: 0.2–1 mm	Yoğun kıyı nüfusu, akarsular, endüstriyel faaliyetler, turizm, yoğun deniz trafiği ve balıkçılık faaliyetleri yer almaktadır.
Yücedağ vd. (2024)	Gemlik Körfezi <u>Balık:</u> 10 tür (123 adet) *Trachurus trachurus Engraulis encrasicolus Diplodus annularis Chelidonichthys lucerna Solea solea Synapturichthys kleinii Scorpena porcus Mullus barbatus Spicara maena Spicara*	Sedimentde: 3333.3–9733.3 parça.kg^{-1} Kuru ağ. Solungaç: 5.38 parça. birey^{-1} Mide bağırsak: 5.49 parça. birey^{-1}	Sediment: PP, PVC, PPS Solungaç: PP, POM, PPS Mide bağırsak: PPS	Lifler	Gemlik Körfezi'ndeki liman faaliyetlerinin, nehir deşarjlarının ve nehir geçişlerindeki mikroplastik kirliliğinin etkisindedir. Ayrıca, endüstriyel faaliyetler ve tarımda etkilemektedir.

	flexuosa Sediment Solungaç Mide - bağırsak İst. Sayısı:15				
Hacısalihoğlu (2025)	Güney Marmara Denizi Balık ve bivalve: 4 tür (660 adet) + 1 tür (50) *Engraulis encrasicolus, Trachurus trachurus, Sardina pilchardus, Sarda sarda Dicentrarchus labrax)* Mide-bağırsak *M. galloprovincialis* İst. Sayısı:5	Balık: toplam 1734 MP tanımlanırken Midye:toplam 650 MP tanımlanmıştır	PE (30%) >PP (30%) >PET (17%) >PVC (14%) >EVA (9%)	Halat ipi parçaları boncuk (%30), elyaf (%20), parça film (%10) 8 Farklı rengte en baskın mor (%28) Turuncu ve siyah Boyut: 0,3 mm'den küçük boyutlar (%44) 1–5 mm (%26)	Bu yüksek değerler muhtemelen bölgedeki yoğun endüstriyel ve kentsel faaliyetlerin bir sonucudur. Kentsel atıklar, gemi trafiği, balıkçılık faaliyetleri ve endüstriyel atıklar bu bölgelerdeki MP yoğunluğunu artırmaktadır.

Ege Denizi’nde gerçekleştirilen Mikroplastik çalışmaları

Referans	Bölge, Örnek Tipi ve İst. sayısı	Partikül miktarı	Plastik Tipi	Plastik şekli, rengi ve boyutu	Kirlilik kaynakları
Yabanlı vd. (2019)	Ege Denizi Datça Yarımadası Kıyı sedimenti İst. Sayısı:4	1154,4 ± 700,3 kg $^{-1}$ (kuru ağ.)	% 60 SBS (Stiren-Bütadien-Stiren Kopolimer), %33,3 PS (Polistiren), PE PP, Naylon, PVCD, EPDM,	parça (%82), film (%9), fibril (%6) pelet (%3) Boyut: >5 mm mavi, beyaz ve siyah	Yoğun turizm faaliyetleri, yat turizmi faaliyetleri ve yaz dönemi nüfus artışı kirliliği tetikleyen etkenler arasındadır.
Aksu vd. (2023)	İzmir Körfezi Sediment İst. Sayısı:10	2.125 - 4.925 adet/m^2 MP	--	Lifler (%65), Renkler siyah (%45) mavi (%23)	İzmir İç Körfezi'ndeki yüksek MP seviyelerine katkıda bulunan etkenler; -Deniz taşımacılığı (feribot ve yolcu iskeleleri), marina faaliyetleri ve tersane faaliyetleri, -Körfezin hidrografik özellikleri (rüzgar ve akıntı dinamikleri), sera faaliyetleri ve plastik geri dönüşüm tesisleri

Şener ve Yabanlı (2023)	Ege Denizi Sahil sedimenti İst. Sayısı:8	Yaz mevsimi: toplam 1490 parçacık (177.11 ± 121.29 parçacık kg $^{-1}$ kuru ağ.) Kış mevsimi : 1389.56 parçacık (170.53 ± 168.87 parçacık kg $^{-1}$ kuru ağ.)	LDP PP	Lif (%61,07), parçacık (%32,12), strafor parçacığı (%2,49), film (%2,38), pelet (%1,94). Mavi (%54,39), beyaz (%22,08), kırmızı (%11,17), yeşil (%4,96), sarı (%4,43) diğer (%2,96) Boyut; 1- 5 mm	Antropojenik faaliyetlere (turizm, balıkçılık ve tarımsal faaliyetler), rüzgar koşullarına ve katı atık yönetimine bağlı olarak değişmektedir. Özellikle yaz dönemi turizm faaliyetleri önemli etken. Ayrıca, girintili çıkıntılı kıyı şeridi, çok sayıda irili ufaklı adanın varlığı, karakteristik olarak farklı Ege ve Akdeniz sularının bu bölgede birbirine karışması, örnekleme alanında makro ve mikroplastik birikimini artırabilecek faktörler olduğunu ifade etmişlerdir.
Aksakal vd. (2021)	Ege Denizi Çeşme/Ildır <u>Bivalve:</u> <u>(30 adet)</u> *Pinctada imbricata radiata* İst. Sayısı:1	Toplamda 65 adet mikroplastik	PE (%92,9) PET (%89,9) PP (%87,8)	% 60 Fiber, % 50 mavi	Antropojenik kirlilik; sentetik kıyafet kaynaklı ikincil tip ya da kozmetik ürünleri (diş macunu, cilt bakım ürünleri vb.) kaynaklı birincil tip evsel atıkların özellikle yaz aylarında artan turizm faaliyetleri sonucu deniz ortamına taşınması.
Yozukmaz (2021)	İzmir Körfezi <u>Bivalve:</u> <u>(60 adet)</u> *M.galloprovincialis* *Ruditapes decussatus* Deniz suyu İst. Sayısı:2	Toplamda 1682 MP adet içermekte. *M.galloprovincialis:*3.90 ± 1.53 *R. decussatus:* 4.15 ± 0.60 parçacık g $^{-1}$ Deniz suyunda toplamda 1832 MP adet içermekte.	--	Bivalve: Lif (%87.22) film (%7.55) Deniz suyunda: Lif (%83.02), film (%8.57) parçacık (%8.41) Renkler: Mavi, kırmızı, sarı baskın renkler Boyut: 0.015-0.1 mm	Covid-19 pandemi dönemindeki ev yasaklarına bağlı olarak, artan evsel atık miktarına bağlı kirliliğin etkisi görülmüştür.

Aksu vd. (2023)	İzmir Körfezi Deniz suyu İst. Sayısı:10	11.083.882 parça/km^2	PE PP	Film(%11,1) lifler (%3,7) köpükler (%3,1) peletler (%0,1) Baskın renk beyaz 0,5-2 mm boyut aralığındaki MP'ler %70,3 ile %71,5	Poligon Deresi'nin deşarjı, deniz taşımacılığı (feribot ve yolcu iskeleleri), marina işletmeciliği ve tersane faaliyetleri gibi yoğun aktivitelerle, belediye atık su arıtma tesislerinden deşarj edilen (kozmetikler, kişisel bakım ürünleri, tekstil) ve özellikle denizcilik uygulamalarında kullanılan bazı boyalardan, ambalaj malzemelerinden kaynaklandığını ifade etmişlerdir.
Gündoğdu vd. (2020)	Ege Denizi Marmara Akdeniz <u>Balık:</u> 5 tür (243 adet) *Chelon saliens,* *M.barbatus barbatus,* *M. surmuletus,* *T.mediterraneus,* *Lithognathus mormyrus* Mide-bağırsak Balıkçılardan toplanmış	1.1 MPs fish^{-1}	PP (%26), PE (%21.9), cellulose (%8.2).	Lif %64.9, parça %35.1 Boyut: 0.028-4.909 mm.	--
Bayhan ve Uncumusaoğlu (2024)	İzmir Körfezi <u>Balık:</u> 8 familya ve 13 tür(366 adet) *S. pilchardus,* *E. encrasicolus,* *B.e svetovidovi,* *C. rhonchus,* *T. mediterraneus,* *T. trachurus,* *M. barbatus,* *M.surmuletus* *B.boops, O. melanurus, S. colias, S. scombrus, S. Solea* Mide-bağırsak	2.21 ± 40.7 adet ind.$^{-1}$	PP (%26), PE (%21.9), PET (%8.2%), cellulose (%7.5)	Lifler Baskın renk siyah Boyut < 3 mm	Körfezdeki atık su arıtma tesisleri, deniz taşımacılığı ve tersanelerin varlığı körfezin MP yükünü artırmaktadır.

	Balıkçılardan toplanmış				
Eryaşar vd. (2024)	İzmir Körfezi Balık: 11 tür (152adet) *S.scombrus* *S. pilchardus* *T.mediterraneus* *M. cephalus* *P. erythrinus* *M.barbatus* *S. aurata* *A.immaculata* *D. labrax* *L. cavillone* *L.mormyrus* Mide-bağırsak Balıkçılardan toplanmış	0,51 ± 0,26 MP ind^{-1}	PE (%45.5) PET (%31.2) PP (%9.1)	Parçacık (% 50,6) lif (% 49,4) Baskın renk siyah. Boyutlar: 101-4901 µm	Deniz ortamında PP ve PE'nin varlığı, gıda ambalajları, ambalaj kağıtları, borular, otomotiv parçaları, yeniden kullanılabilir torbalar, tarımsal filmler ve şişeler gibi endüstriyel tüketim mallarının yaygın kullanımından kaynaklandığı ifade edilmiştir.
Koraltan vd. (2024)	Datça-Bozburun Özel Çevre Koruma Bölgesi Deniz suyu İst. Sayısı: 17	132 microplastics (1.49±1.11 mm) 6 mesoplastics (6.63±1.62 mm) MPs bolluğu 10 – 6.7m^{-3}	EPCs (%37.5) PET (%16.7)	Lif (%93.9), gemilerin dış boya parçacıklarından (%3.8) filmden (%2.3) Baskın renkler mavi (%23.5) kırmızı (%5.3).	MP kirliliği, öncelikle yerleşim alanları, sanayi siteleri ve tatil tesisleri gibi insan faaliyetlerinin yoğun olduğu üç bölgede gözlemlenmiştir. Diğer üç bölgede ise kirliliğin hem insan faaliyetleri hem de tarım alanları ve liman tesisleriyle bağlantılı olduğu belirlenmiştir.
Özkan vd. (2025)	Ege Denizi Sediment İst. Sayısı:16	2979 ± 1560 adet/kg kuru tortu.	PE PP	Parçalar (%59,54), lifler (%36,77), filmler (%3,55) Baskın renk şeffaf (%52) Boyut: 0.73 ± 0.98 mm, çoğunlukla < 1 mm	Endüstriyel atıklar, evsel atıklar, deniz trafiği en etken kirlilik kaynaklarıdır.

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Chapter 2

Food Safety in Seafood: The Use of Bacteriophages for Biocontrol

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1. Introduction

As a rich source of highly bioavailable proteins and essential minerals, seafood plays a crucial role in human nutrition. The per capita seafood supply is projected to reach 21.4 kg by 2030. However, these products are highly susceptible to microbial contamination during the stages of harvesting, handling, storage, processing, and distribution. In addition to spoilage bacteria such as Pseudomonas, Acinetobacter, and Serratia, pathogens like *Escherichia coli*, *Listeria monocytogenes*, *Clostridium botulinum*, *Staphylococcus aureus*, *Salmonella* Typhimurium, *Vibrio vulnificus*, *Vibrio cholerae*, and *Vibrio parahaemolyticus* can also be transmitted to humans through seafood, posing serious health risks (Yan et al., 2024). Therefore, the implementation of effective microbial control methods is of great importance to preserve the quality and safety of seafood.

2. Microbial Risks

Despite their high nutritional value, seafood is highly susceptible to microbial contamination (Elbashir et al., 2018). The microbial load can originate from both the natural microflora of marine and fresh waters and from land-based contaminants. While the natural water microflora includes species such as Acinetobacter, Aeromonas, Alteromonas, Bacillus, Clostridium, Flavobacterium, Pseudomonas, Shewanella, and Vibrio, contaminants of human and animal origin include Enterococcus, *E. coli*, Salmonella, Klebsiella, Shigella, and Yersinia. Furthermore, cross-contamination can occur during processing and distribution stages due to inadequate hygiene, contaminated

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equipment, and personnel. This situation increases the microbial load of both raw and processed products (Parlapani, 2021).

2.1. Pathogenic Microorganisms The most common bacterial pathogens in seafood include Vibrio species (*V. vulnificus*, *V. parahaemolyticus*, *V. cholerae*), *L. monocytogenes*, *Salmonella* spp., *C. botulinum*, and *Shigella* spp. (Elbashir et al., 2018).

- **Vibrio species:** Transmitted through raw or undercooked shellfish, these pathogens can cause a range of health problems, from gastrointestinal disorders to systemic infections. *V. vulnificus* exhibits virulence through its capsule, hemolysins, type IV pili, and metalloproteases, while *V. parahaemolyticus* displays virulence via the *tdh* and *trh* genes. Furthermore, *V. cholerae* and *Vibrio mimicus* can cause cholera outbreaks through their toxigenic O1 and O139 serotypes (Elbashir et al., 2018).
- ***Listeria monocytogenes:*** This is a Gram-positive, non-spore-forming bacterium capable of forming biofilms. It can survive within a wide range of temperatures and pH levels. It is primarily transmitted to humans through ready-to-eat foods and poses a particular risk in raw or lightly processed seafood (Feldhusen, 2000; Elbashir et al., 2018).

- ***Salmonella spp.:*** This is a Gram-negative, motile, and enterotoxin-producing bacterium. It can be transmitted through raw or undercooked fish and shellfish and also carries a risk of cross-contamination during processing. Although antimicrobial-resistant strains exist, these risks can be mitigated through the implementation of Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP) systems (Salama and Chennaoui, 2024).

- ***Clostridium botulinum:*** This is a Gram-positive, spore-forming bacterium that produces potent neurotoxins. Types A, B, E, and F are responsible for the majority of foodborne botulism cases. Its spores are resistant to high heat and can produce toxins even at low temperatures. This characteristic creates a serious public health risk, especially in processed, salted, and fermented products (Elbashir et al., 2018; Salama and Chennaoui, 2024).

- ***Shigella spp.:*** Species such as *Shigella dysenteriae*, *Shigella flexneri*, *Shigella boydii*, and *Shigella sonnei* can be transmitted through contaminated water or by cross-contamination during processing. As a human-specific pathogen, Shigella causes diarrhea and dysentery, particularly in children and immunocompromised individuals. Good manufacturing practices and cold chain control significantly reduce the risk of transmission (Salama and Chennaoui, 2024).

2.2. Spoilage Microorganisms

In fish and fishery products, microorganisms such as Pseudomonas, Shewanella, Flavobacterium, Photobacterium, Alcaligenes, Aeromonas, Enterobacter, Bacillus, Enterococcus, Psychrobacter, *E. coli*, and Brochothrix are among the species that frequently cause spoilage. Although these bacteria are not pathogenic, they shorten the shelf life of the products, leading to quality degradation and economic losses (Feldhusen, 2000; Parlapani et al., 2021; Tahiluddin et al., 2022).

Therefore, the effective control of both pathogenic and spoilage microorganisms in seafood is of critical importance, not only for protecting public health but also for preventing economic losses.

3. Innovative Microbial Control Technologies

Traditional processing methods such as smoking, drying, fermentation, canning, and salting are widely used. However, these processes can lead to significant changes in the physicochemical properties of the products; examples include protein denaturation, vitamin losses, color alterations, and disruption of the natural microbiota (Li et al., 2014). To overcome these issues, non-thermal technologies such as high hydrostatic pressure, pulsed electric fields, cold plasma, pulsed light, irradiation, and ozonation have been developed in recent years. These approaches preserve the sensory and nutritional qualities of products, such as colour, flavour and texture, while extending their shelf life. However, large-scale implementation remains challenging due to high operational costs, the need for specialised equipment and technically skilled personnel (Yan et al., 2024). Efforts to reduce the microbial load, particularly in raw and delicate products like fresh fruits, vegetables, and seafood, involve various decontamination strategies that encompass both thermal and non-thermal methods; however, these approaches are not always sufficient due to their inherent limitations. Therefore, there is a need for more efficient, safe, and environmentally friendly approaches to reduce food contamination (Yan et al., 2024; Braz et al., 2025).

4. Antibiotic Resistance and the Importance of Phages

Antibiotics are among the most effective chemical agents for controlling bacterial pathogens. However, the emergence and subsequent spread of resistant microorganisms is progressively reducing the effectiveness of pathogen control. The introduction of antibiotics for treating and controlling infectious diseases marked a milestone in the evolution of modern medicine. However, the misuse of these antimicrobial agents has led to the development of resistance in both pathogenic and spoilage-causing microorganisms (Lee et al., 2023; Wu-Wu et al., 2023).

Antibiotics are widely used not only for human health but also in livestock farming to promote animal growth. This situation leads to the emergence of antibiotic-resistant foodborne pathogens that can reach humans through the food supply chain (Kaur et al., 2016; Okaiyeto et al., 2024). In agriculture, the use of antibiotics is applied not only to prevent infections but also to accelerate animal growth in order to meet the increasing demand for meat and milk. Consequently, bacterial antimicrobial resistance has become a global problem in both the health and agricultural sectors, with resistant bacterial strains posing a serious threat to both animal and human health (McDermot et al., 2006). Indeed, according to data from the Centers for Disease Control and Prevention (CDC), foodborne illnesses in the United States alone are associated with approximately 76 million cases, 325,000 hospitalizations, and 5,000 deaths annually (Kaur et al., 2016).

The widespread use of antibiotics in agriculture and animal husbandry has also raised concerns about residual antibiotic contamination in foods. This situation accelerates the natural evolution of antibiotic resistance in pathogenic microorganisms and poses a global threat to food safety. The detection of new antibiotic-resistant bacteria (ARB) strains in foods of plant and animal origin in recent years indicates that the problem is growing. These bacteria can be transmitted to humans through direct contact with infected animals or the consumption of contaminated foods (Okaiyeto et al., 2024).

The intensive and inappropriate use of antibiotics has led to the emergence of multi-drug resistant zoonotic pathogens, a situation that has increased scientific and public scrutiny. Various studies show that the use of antibiotics in livestock farming is associated with the transmission of resistant foodborne bacteria to humans (McDermot et al., 2006).

Therefore, developing alternative biocontrol strategies to antibiotics is of critical importance. Bacteriophages, antimicrobial peptides, and probiotics offer effective and environmentally friendly solutions against resistant bacteria. Although the use of phage therapy declined in Western countries with the proliferation of antibiotics, it is still practiced as an important treatment method in some parts of Eastern Europe. The rise in antibiotic resistance has increased the need for new therapeutic approaches and has spurred the development of bacteriophage applications in the fields of health, veterinary medicine, and agriculture in Europe and the USA (Monk et al., 2010; Golkar et al., 2014; Wu-Wu et al., 2023). The table below summarizes the advantages and limitations of phages compared to antibiotics (Sulakvelidze et al., 2001).

Table 1. Advantages and limitations of phages and antibiotics (Sulkvelidze et al., 2001)

Feaure	Phages	Antibiotics	Comments
Specificity	Their activity is largely restricted to the intended bacterial hosts, which helps preserve microbial homeostasis and prevents secondary infections	By targeting both pathogens and the normal microbiota, they may alter the microbial balance and consequently facilitate the development of secondary infections.	High specificity can be a limitation; the causative bacterium must be identified before phage therapy. Antibiotics may be preferable if the agent is unknown
Local replication	Replicate at the site of infection, concentrating where most needed	Metabolized and eliminated; do not necessarily accumulate at the infection site	Exponential growth of phages at the infection site may reduce administration frequency for optimal effect
Side effects	No serious side effects reported	Many side effects reported, including intestinal disorders, allergies, secondary infections	Minor phage side effects may result from endotoxin release due to bacterial lysis; similar effects can occur with antibiotics
Resistance	Bacteria resistant to one phage often remain susceptible to other phages with similar host range	Antibiotic resistance is not limited to the targeted bacteria	Antibiotics select resistant mutants of targeted bacteria and many other resistant species due to broad-spectrum activity
Development of new agents	Selection of new phages (e.g., against phage-resistant bacteria) is relatively fast, often completed within days or weeks	Development of a new antibiotic is time-consuming, often taking several years	Active phages can be naturally selected against any resistant bacteria, whether antibiotic- or phage-resistant

5. The Importance of Bacteriophages

Bacteriophages are one of the most prominent innovative biocontrol methods today (Li et al., 2014; Vikram et al., 2022). Bacteriophages are viruses that can specifically infect and replicate within target bacteria. As some of the most abundant organisms on Earth, the number of phages is estimated to be approximately 10^{32}, and these viruses, along with their bacterial hosts, play important ecological roles in all natural environments (Lasagabaster et al., 2020; Braz et al., 2025). Phages are consumed by humans through the natural microbiota in various foods, including seafood. Because they target specific bacteria, they only affect pathogens without harming the beneficial microflora or host cells (Yan et al., 2024).

Bacteriophages are notable for their low production costs. They can be used in combination with other antimicrobial methods and can be preserved during storage by being integrated into food packaging materials. These characteristics make them an attractive biocontrol agent. Furthermore, the increasing consumer demand for raw or undercooked seafood further enhances the importance of phages (Rindhe et al., 2024).

Phages are effective against pathogens such as Salmonella, Listeria, and *E. coli*, as well as against food spoilage bacteria like Pseudomonas, *Brochothrix thermosphacta*, and Shewanella (Hernandez, 2017). Research indicates that phages do not alter the sensory properties of food, are safe for human consumption, and are compatible with practical application conditions (Yan et al., 2024).

6. Structure and Life Cycles of Bacteriophages

Bacteriophages are small viruses, measuring approximately 24-400 nm, that specifically infect and replicate within target bacterial hosts. They consist of a proteinaceous capsid enclosing their genetic material, which may be single- or double-stranded DNA or RNA, and often possess a tail structure appended to the capsid. Receptor-binding proteins located at the distal end of the tail mediate recognition of specific receptors on the bacterial surface. The vast majority of bacteriophages (>96%) are classified within the order *Caudovirales*, characterized by icosahedral capsids containing double-stranded DNA and an associated tail. This order is further subdivided into three families: *Myoviridae*, featuring long contractile tails; *Siphoviridae*, with long non-contractile tails; and *Podoviridae*, exhibiting short non-contractile tails. Other bacteriophages display cubic, filamentous, or pleomorphic morphologies (Lasagabaster et al., 2020).

According to their life cycles, bacteriophages are classified as either virulent or temperate. Virulent phages exhibit a lytic cycle; after transferring their genetic material into the host cell, they hijack the cell's metabolism, produce new phage particles, and kill the bacterial cell through lysis, releasing the new virions. In contrast, temperate phages exhibit a lysogenic cycle; their genetic material integrates into the host cell genome (as a prophage) and replicates passively. They can also prevent other phage infections in the same host, thereby delaying bacteriolysis. The induction or excision of the prophage from the host genome, either spontaneously or in response to internal or external cellular triggers, can initiate the lytic cycle, allowing the progeny phages to lyse other susceptible bacteria (Figure 1). However, temperate phages do not kill bacteria immediately and can confer new functional genes, such as virulence or antibiotic resistance genes, through integration into the host genome. Therefore, unmodified temperate phages should not be used in therapeutic biocontrol applications. These characteristics are the primary reason why only virulent phages are considered suitable for biocontrol (Batinovic et al., 2019; Lasagabaster et al., 2020).

Phages utilized within the food industry are predominantly virulent types that undergo a lytic replication cycle. This cycle encompasses five distinct phases—adsorption, penetration, replication, maturation, and lysis. During adsorption, the interaction proceeds through sequential stages of initial contact, reversible attachment, and finally, irreversible binding to the bacterial surface. While initial contact occurs through random collisions, reversible binding involves weak interactions with primary receptors, and irreversible binding involves strong, permanent interactions with secondary receptors. Following penetration, the phage genome is transferred into the host cell, and the host's metabolism is redirected to produce phage nucleic acids and proteins. The release of new phage particles occurs through lysis. Double-stranded DNA phages (e.g., *Caudovirales*) use multiple proteins for lysis, such as holin, endolysin, and spanin, whereas single-stranded DNA and RNA phages initiate lysis with a single protein (Yan et al., 2024).

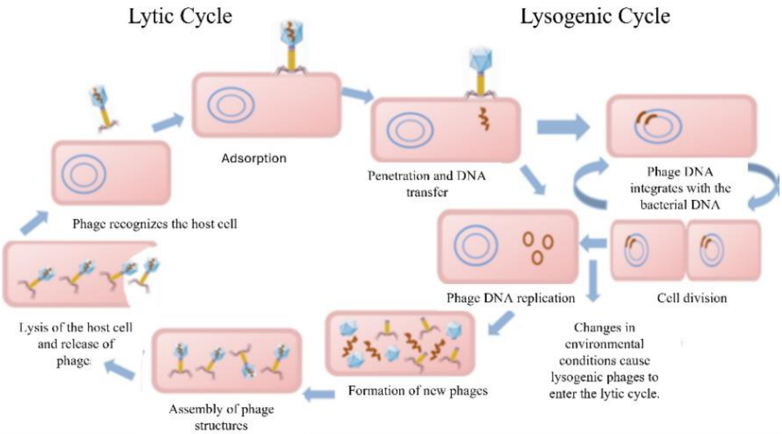

Figure 1. Lytic and lysogenic cycle (Batinovic et al., 2019; Gündüz 2021).

7. Discovery and Historical Background of Bacteriophages

The antibacterial properties of phages were first discovered by Ernest Hanbury Hankin in 1896. Hankin reported that a heat-sensitive and filterable substance exhibiting antibacterial activity against *V. cholerae* was responsible for limiting cholera outbreaks. A similar phenomenon was observed in 1898 by the Russian bacteriologist Gamaleya during studies conducted with *Bacillus subtilis* (Sulakvelidze et al., 2021; Yan et al., 2024).

Modern discovery of bacteriophages is attributed to the British bacteriologist Frederick Twort in 1915 and to Félix d'Herelle in 1917. Twort observed a glassy transformation in bacterial colonies grown in culture media and proposed the existence of a minute virus that inhibited bacterial growth. D'Herelle, on the other hand, identified this agent exhibiting antagonistic activity against bacteria and named it "bacteriophage." The term *bacteriophage* is of Greek origin and literally means "bacteria eater" (Sulakvelidze et al., 2021).

The morphological structure of bacteriophages was examined in detail in 1940 with the use of the electron microscope (Ankerman, 2003). During the first half of the twentieth century, several companies began the commercial production of phages intended for use against human pathogens. D'Herelle's laboratory in Paris produced preparations containing five different phages for various bacterial infections, which were marketed by "L'Oréal." In the United States, by 1940, seven phage preparations had been developed against *Staphylococcus*, *Streptococcus*, *E. coli*, and other bacterial pathogens. However, with the discovery of antibiotics, phage therapy was largely abandoned in Western countries, whereas research on phages continued in the former Soviet Union and Poland (Sulakvelidze et al., 2021).

In recent years, the rise of antibiotic resistance and advances in biotechnology have led to the renewed interest in bacteriophages. Today, phages are being considered potential antimicrobial agents for the treatment of bacterial diseases in humans, animals, and plants (Ofir and Sorek, 2018; Jamal et al., 2019).

8. Application of Bacteriophages in Food Safety

Phage-based applications targeting specific pathogens in foods have been increasingly recognized as a natural and environmentally friendly food safety strategy, commonly referred to as "bacteriophage biocontrol" (Moye et al., 2018; O'Sullivan et al., 2019; Lasagabaster et al., 2020).

In 2006, the U.S. Food and Drug Administration (FDA) approved the first phage products for use in food processing (ListShield™, Intralytix, Baltimore, MD, USA) (Yan et al., 2024). Subsequently, products such as Listex™

(currently PhageGuard Listex™), SalmoFresh™, and PhageGuard S™ received GRAS (Generally Recognized As Safe) status and began to be applied across various food sectors, including meat, poultry, egg, and seafood industries (Vikram et al., 2022; Narayanan et al., 2024). Moreover, the U.S. Department of Agriculture (USDA) classified these products among safe food ingredients. Following these regulatory steps in the United States, similar approval processes were implemented in several other countries, including Israel, Canada, Switzerland, Australia, New Zealand, and members of the European Union, where phage products have been officially recognized as legitimate biocontrol tools in food safety (Narayanan et al., 2024).

9. Application of Bacteriophages in Aquatic Products

In response to increasing food safety concerns in recent years, bacteriophages have emerged as safe and effective biocontrol agents for managing pathogenic and spoilage bacteria. Consequently, phage applications are being increasingly investigated at different stages of the seafood production chain and can be implemented within the framework of the "Farm-to-Fork" approach (Kazi and Annapure, 2016; Moye et al., 2018; Yan et al., 2024) (Figure 2).

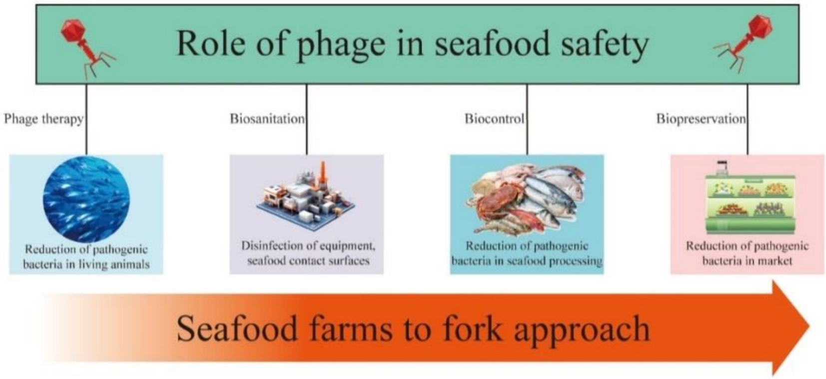

Figure 2. Application of bacteriophages within the seafood production chain (Yan et al., 2024).

Vibrio species are widespread Gram-negative bacteria inhabiting aquatic and coastal ecosystems, capable of causing economic losses in aquaculture as well as infections in humans (Yan et al., 2024). Studies on *V. parahaemolyticus* have demonstrated the promising potential of phage therapy. For instance, You et al. (2021) reported that the lytic phage VPT02 was effective against antibiotic-resistant strains and increased shrimp survival rates from 16.7% to 46.7%. Ren et al. (2019) found that the phages PVP1 and PVP2 provided greater protection in sea cucumbers compared to antibiotics. Similarly, Lee et al. (2023) demonstrated that the phage VPG01 completely eliminated the pathogen in fish meat within six hours. Kim et al. (2024) reported that the Vibrio-specific phage CAU-VPP01 significantly reduced biofilm formation in squid and mackerel, decreasing biofilm biomass, thickness, and roughness. Furthermore, Zheng et al. (2024) genomically characterized five virulent *V. parahaemolyticus* phages (VPpYZU64, VPpYZU68, VPpYZU81, VPpYZU92, and VPpYZU110) and evaluated their bacteriostatic effects in combination with citric acid. The study revealed that the combination of phages and citric acid significantly reduced *V. parahaemolyticus* counts and inhibited biofilm formation on salmon fillets, indicating that the combined use of phages with organic acids may represent a natural and effective strategy for pathogen control in seafood.

Studies on *V. cholerae* have shown that the efficacy of phage therapy increases when applied in combination with high hydrostatic pressure (HHP). Ahmadi et al. (2025) reported that phage treatment alone resulted in a reduction of 1.2 log_{10} CFU/g, whereas its combination with HHP achieved a reduction of 2.6–3.3 log_{10} CFU/g. Against *V. vulnificus*, one of the most virulent Vibrio species, Pelon et al. (2005) demonstrated that combining phages with oyster extracts reduced the pathogen load from 10^6 to 10^1 CFU/mL. Similarly, Kim et al. (2021) found that the phage VVP001 reduced *V. vulnificus* counts by 2.06–2.51 log CFU/mL at different multiplicities of infection (MOI) and inhibited bacterial growth for up to 8 hours. Furthermore, studies on *Vibrio harveyi* reported that the phages VB-VhaP-Vh-5 and VB-VhaP-Vh-8 increased the survival rate of infected turbot (*Scophthalmus maximus*) without negatively affecting normal growth (Cui et al., 2021).

Salmonella Typhimurium is a common foodborne pathogen that causes acute gastroenteritis and can lead to more severe infections, such as septicemia, in immunocompromised individuals. Pereira et al. (2016) investigated the effects of phages phSE-2, phSE-5, and their combination in shellfish, and found that single phage suspensions at low multiplicities of infection (MOI) were more effective against *S.* Typhimurium. However, under conditions of natural contamination, both single phages and phage mixtures resulted in approximately 0.7-0.9 log CFU/g reductions within 6 hours. In artificially contaminated shellfish, the phage phSE-5 achieved a 2.0 log CFU/g reduction after 6 hours, compared with only a 1.1 log CFU/g reduction in untreated controls. Xu et al. (2018) evaluated the efficacy of bacteriophage SLMP1 on raw salmon fillets and scallops, reporting that during storage at 4 °C, the phage reduced *Salmonella* counts to below the detection limit or maintained them at low levels.

L. monocytogenes is an important pathogen in seafood due to its ability to grow under low temperature, high salt, and acidic conditions. To control this bacterium, the FDA has approved the phage preparations ListShield™ and Listex P-100™ (Yan et al., 2024). Studies have shown that phages are effective both alone and in combination with other treatments. For example, the phage SH 3-3 isolated by Zhou et al. (2020) inhibited biofilm formation and reduced *L. monocytogenes* counts by 4.54 log over 72 hours in raw salmon. Banos et al. (2016) reported successful application of phage P100 combined with AS-48 in cod and salmon, while Gündüz and Öztürk (2021) demonstrated that applying Listex P100™ in sodium alginate films on smoked trout surfaces suppressed Listeria growth. Furthermore, the application of Listex™ P100 in traditional fermented fish products (Rakfisk) resulted in approximately 0.9 log reduction of *L. monocytogenes* at 7-8 °C, highlighting temperature as the most critical factor for growth; approximately 2 log increase was observed at 7 °C, whereas growth was limited at 4 °C (Axelsson et al., 2020).

Pseudomonas species, widespread in soil, water, and food processing environments, contribute to spoilage in seafood through the production of volatile compounds such as aldehydes, ketones, and esters. In particular, *Pseudomonas fluorescens* and *Pseudomonas putida* are notable for their strong biofilm-forming capabilities (Yan et al., 2024).

Shewanella putrefaciens is a Gram-negative species adapted to low temperatures and recognized as a dominant spoilage bacterium in chilled seafood, producing biogenic amines (putrescine, cadaverine) and off-odors (trimethylamine, H_2S) that reduce product quality. Yang et al. (2019) demonstrated that a phage cocktail (SPMIX3-156) combining three phages (SppYZU01, SppYZU05, SppYZU06) effectively inhibited *Shewanella* growth in turbot suspensions at both 25 °C and 4 °C.

These findings collectively indicate that phages provide a safe and natural biocontrol strategy by targeting pathogens and spoilage bacteria in seafood. Their use, particularly during harvesting, transport, processing, and distribution, can reduce contamination risks and help prevent economic losses (Yan et al., 2024).

10. Limitations of Phage Applications

Bacteriophages have emerged as promising biocontrol agents for managing pathogenic and spoilage bacteria in the food safety and aquaculture sectors.

However, the widespread implementation of phage applications in the food production chain faces several limitations (Table 2).

Issue / Limitation	Description	Possible Solution	References
Public Acceptance	Consumers often perceive phages as viruses and approach their application with suspicion due to lack of knowledge.	Awareness and educational programs about phages can be enhanced.	Yan et al., (2024) Endersen and Coffey (2020)
Stability	Phage stability may be compromised under low temperatures, high salt, or acidic conditions.	Phages can be protected using microencapsulation, liposomes, or polymer-based carriers.	Ge et al., (2022) Liu et al., (2024)
Safety	Some phages may carry antibiotic resistance genes or virulence factors.	Only lytic and genetically well-characterized phages should be used.	Amjad et al., (2024)
Resistance Development	Target bacteria can rapidly develop resistance to single or combined phages.	Use of phage cocktails with different strains and isolation of new highly effective phages is recommended.	Yan et al., (2024) Endersen et al., (2020)
Efficacy / MOI	Phage capacity to completely eliminate pathogens depends on multiplicity of infection (MOI) and the application method.	Phages can be combined with other bactericidal methods (e.g., organic acids, HHP) to enhance effectiveness.	Ge et al., (2022) Liu et al., (2024)

Table 2. Challenges in phage applications and proposed solutions

In conclusion, although bacteriophages hold considerable potential in food safety, their application should take into account limitations such as stability, resistance development, safety, and consumer perception. To overcome these challenges, advanced microencapsulation techniques, phage cocktails, and combined applications with other biocontrol strategies are increasingly important (Yan et al., 2024; Liu et al., 2024).

11. Conclusion

Bacteriophages provide a safe, natural, and sustainable biocontrol strategy by targeting pathogenic and spoilage bacteria in seafood (Moye et al., 2018; Yan et al., 2024). Due to their high specificity, they affect only target bacteria, leaving beneficial microflora unharmed, and help extend product shelf life while preventing quality loss (Banos et al., 2016). Commercially developed preparations such as Ecoshield™, ListShield™, Listex™, and Salmonlex™ have demonstrated efficacy in controlling major pathogens including *E. coli*, *L. monocytogenes*, and Salmonella (Kazi and Annapure, 2016). These findings indicate that phages can play a critical role in seafood safety, both from a public health and an economic perspective.

However, several limitations hinder the widespread application of phages. Phage resistance, complex conditions in aquatic environments, and consumer perception are among the factors that constrain their broader use (Strauch et al., 2007). Consequently, research emphasizes the careful selection of appropriate phage strains, optimization of storage conditions, and integration with other biotechnological approaches such as probiotics or biofilm technologies (Baginska et al., 2024; Soffritti et al., 2025).

In the future, the targeted design of phages through advanced genetic engineering and synthetic biology techniques is expected to create new opportunities in the seafood industry by enhancing efficacy and specificity. These strategies hold significant potential to overcome the limitations of conventional methods, reduce antibiotic use, slow the emergence of resistant bacteria, and improve food safety (Yan et al., 2024).

In conclusion, bacteriophages are increasingly recognized as a critical tool in seafood safety, complementing existing biocontrol methods and offering more sustainable and environmentally friendly solutions for the future.

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Chapter 3

Digestive Enzymes Formed During the Larval Stage of Marine Fish

Sevim HAMZAÇEBİ[1]

1. Introduction

Aquaculture has emerged as the fastest-growing animal food production sector globally and holds considerable potential for continued growth in the future (Guillen et al., 2019). Technological advancements have significantly boosted the production volume of aquaculture derived aquatic products. Based on current trends and research, it is anticipated that the volume of aquaculture-derived seafood will continue to grow, potentially surpassing that obtained through capture fisheries by 2030. According to forecasts, production is expected to reach 106 million tons by that time (FAO, 2022; Lubchenco et al., 2020).

In recent years, there has been a growing emphasis on increasing both the quantity and quality of aquaculture production. In this context, research in biotechnology particularly in enzymology, genetics, and histology has gained prominence. Findings from such studies have become directly applicable to the production process, informing efforts to enhance larval and juvenile quality, increase survival rates, improve feed utilization and specific growth rates, strengthen immunity against diseases, and develop optimal feeding strategies under varying environmental conditions. Physiological changes that directly influence larval and juvenile quality in aquaculture typically occur during the larval stage, including both embryonic and ontogenetic development (Papandroulakis et al., 2004).

One of the key objectives of researchers and producers alike is to minimize mortality arising from biotic and abiotic factors during this critical stage. A detailed understanding of the complex physiological events that occur during larval development has only become possible with advancements in biotechnology and its integration into aquaculture. This development process is

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crucial for improving larval survival and the quality of juvenile fish (Valente et al., 2013).

It is also crucial to comprehend the nutritional needs of other species that are being targeted for production. During the larval stage, the activity of digestive enzymes plays a critical role in developing species-specific feeding strategies to increase survival rates.

2. Enzymes

Enzymes are protein-based biocatalysts that enable biochemical reactions to occur under favorable conditions without causing harm to the organism. A catalyst is a substance that accelerates a chemical reaction without being consumed or altered in the process (Dinçkaya, 1997b). For vital life functions to continue, hundreds of metabolic reactions must occur within living organisms, most of which take place intracellularly. The high temperatures that could result from these reactions would damage proteins and harm the organism. The presence of enzymes allows these reactions to proceed efficiently under mild, organism-compatible conditions with low energy input (Trevor Palmer, 1985; Gözükara, 1997).

2.1. Characteristics of Enzymes

Enzymes do not need to remain within the cells where they are produced to be active. They are synthesized by living cells under biological conditions and are typically large, structurally complex protein molecules. The sequence of amino acids in a protein, determined by the organism's genetic code, governs the enzyme's specific structure and function. This specific amino acid arrangement is key to the enzyme's substrate specificity and its quaternary structure. As a result, enzymes act as regulators of countless chemical reactions involved in intermediary metabolism.

To perform their function, enzymes may require coenzymes or cofactors. The product of one enzyme-catalyzed reaction often becomes the substrate for another, forming reaction chains that play a critical role in cellular metabolism regulation (Trevor Palmer, 1985; Karlson, 1992; Gözükara, 1997).

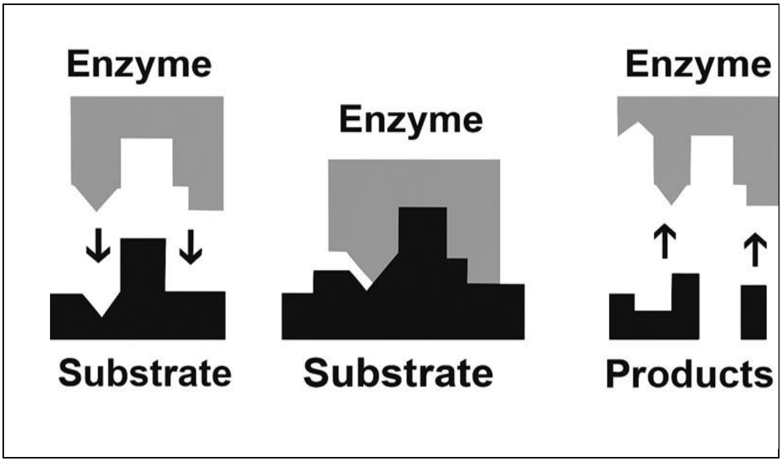

Figure 1. Substrate-Enzyme mechanism (Gözükara, 1997).

2.2. Structure and Classification of Enzymes

In certain cases, for enzymes to exhibit catalytic activity, they require both a coenzyme and a cofactor, which may bind to the enzyme loosely or through covalent bonds (Dinçkaya, 1997b). These non-protein components, tightly bound to the enzyme's surface, are called prosthetic groups.

The organic molecules essential for enzymatic activity are termed coenzymes, while cofactors generally refer to metal ions that are not protein-based but are crucial for the catalytic function. Vitamins often constitute the structural basis of coenzymes. Hence, vitamins are indispensable to organisms because they facilitate rapid and efficient enzymatic reactions by participating in metabolic pathways.

Common examples of coenzymes include NAD (Nicotinamide Adenine Dinucleotide), FAD (Flavin Adenine Dinucleotide), and NADP (Nicotinamide Adenine Dinucleotide Phosphate) all of which act as hydrogen carriers. Additionally, metal ions such as Ca^{2+}, Mg^{2+}, Zn^{2+}, K^{+}, Na^{+}, Cu^{2+}, and Fe^{2+} serve as cofactors for numerous enzymes (Trevor Palmer, 1985; Karlson, 1992, Gözükara, 1997).

An enzyme is called a holoenzyme when it is completely catalytically active and coupled to its corresponding coenzyme or cofactor. An apoenzyme, which is made entirely of its protein portion, is an enzyme that loses its function when the cofactor or coenzyme is removed.

The International Enzyme Commission (EC) has established three primary principles for naming enzymes:

1. Enzyme names typically end in "–ase", which applies primarily to enzymes catalyzing a single reaction, and is not suited to multi-enzyme complexes.
2. Enzymes are named and classified based on the type of reaction they catalyze. Hence, systematic naming is only possible once the enzyme's catalytic function is fully understood.
3. The EC naming convention, even if the reaction is reversible, only reflects the direction considered in the classification. Proposed names, however, often take into account the directionality of reactions in biological systems.

According to the 1961 report by the Enzyme Commission, enzymes are categorized into six major classes based on the type of reaction they catalyze. Each enzyme is designated an EC number, comprising four digits:

- **First digit**: Indicates the major enzyme class
- **Second digit**: Denotes the subclass
- **Third digit**: Specifies the sub-subclass
- **Fourth digit**: Represents the serial number of the enzyme in that group

Examples:

- *Trypsin*: EC 3.4.21.4
- *Amylase*: EC 3.2.1.1
- *Lipase*: EC 3.1.1.3

2.3. The Six Major Enzyme Classes

1. **Oxidoreductases**: Enzymes that catalyze oxidation-reduction reactions. Those that utilize oxygen as an acceptor are termed oxidases. *Example*: Lactate dehydrogenase (LDH).
2. **Transferases**: Enzymes transferring specific functional groups (e.g., methyl, acyl, amino, glycosyl, phosphate) from one molecule to another. *Example*: Glucokinase.
3. **Hydrolases**: Enzymes catalyzing hydrolytic cleavage of C–O, C–N, C–C, and other bonds.
   Examples: Trypsin, chymotrypsin, lipase.
4. **Lyases**: Enzymes that remove groups from molecules by mechanisms other than hydrolysis, typically via elimination reactions. *Examples*: Pyruvate decarboxylase, carbonic anhydrase.
5. **Isomerases**: Enzymes catalyzing structural rearrangements within molecules (e.g. geometric or positional isomerism).

Examples: D-glucose-6-phosphate ketol-isomerase, D-glyceraldehyde-3-phosphate ketol-isomerase.

6. **Ligases**: Enzymes that join two molecules using energy derived from the hydrolysis of ATP or other nucleoside triphosphates. *Examples*: Asparagine synthetase, acetyl-CoA carboxylase.

2.4. Factors Affecting Enzyme Activity

Enzyme activity is defined by the degree of catalytic activity that an enzyme demonstrates within a biological system, not by the quantity of enzyme present. In biological contexts, enzymes usually exist in extremely small amounts and work by speeding up chemical reactions.

Under standard conditions (25°C), the amount of enzyme that converts 1 micromole of substrate into product per minute is defined as 1 enzyme unit. However, enzymatic reactions do not operate with the same efficiency under all conditions. Since enzymes are protein-based molecules, their activity is significantly influenced by environmental parameters.

The following factors play a key role in determining enzyme activity:

1. Temperature

The optimal temperature range for most enzymes lies between 25°C and 37°C. Given that enzymes are protein-based, they are highly sensitive to temperature fluctuations.

- High temperatures can lead to protein denaturation, causing irreversible loss of enzyme function.
- Low temperatures, although they do not denature enzymes, render them temporarily inactive.

This is why enzyme preparations are commonly stored at very low temperatures (between –80°C and –20°C) to preserve their activity.

2. pH Level

The rate of enzyme-catalyzed reactions varies with the hydrogen ion concentration (pH) of the medium. Each enzyme has an optimum pH at which it performs most efficiently. Deviation from this optimal pH, whether towards acidic or basic extremes, can slow down or halt the reaction.

To maintain this optimal pH, buffer solutions are typically added during enzyme preparation.

Examples of optimal pH ranges:

- **Trypsin & Chymotrypsin**: pH 8–11

- **Amylase**: pH 5.6–7.2
- **Lipase**: pH 7
- **Pepsin**: pH 1.5–2.5

3. Enzyme Concentration

When the substrate concentration is abundant and constant, the reaction rate increases linearly with enzyme concentration. This is due to the fact that enzymes operate independently of one another more enzyme molecules result in more simultaneous reactions.

4. Substrate Concentration

Once the enzyme binds to a substrate to form the enzyme-substrate (ES) complex, the substrate is converted into product and the enzyme is released to act again.

As the substrate concentration increases:

- The likelihood of enzyme-substrate collisions increases.
- This leads to a faster reaction rate until the enzyme becomes saturated.

The availability of the substrate affects the reaction rate when the enzyme concentration is fixed.

5. Time

Enzymatic activity is often measured by the amount of product formed over a given time. The standard measurement period for activity assays is typically 5 minutes.

Prolonging the reaction time may:

- Lead to pH shifts in the medium.
- Cause enzyme denaturation due to accumulation of reaction products.

6. Effect of Ions and Other Chemicals

Some enzymes, especially digestive enzymes, are synthesized in an inactive form (proenzymes). To become active, these require specific ions or enzymatic reactions.

- The presence of heavy metal ions in the reaction medium can inhibit enzyme activity by binding to the enzyme.
- Many digestive enzymes are produced in precursor forms (e.g., zymogens), which only become active after cleavage of specific peptide bonds.

2.5. Proenzymes and Activation

Digestive enzymes that break down proteins are initially synthesized in inactive forms by the pancreas and stomach. These proenzymes become active enzymes upon structural modification, usually triggered by environmental conditions in the digestive tract.

Table 1. Major Proteolytic Enzymes Synthesized as Proenzymes

Proenzyme	Synthesized In	Active Enzyme
Trypsinogen	Pancreas	Trypsin
Chymotrypsinogen	Pancreas	Chymotrypsin
Pepsinogen	Stomach	Pepsin
Procarboxypeptidase	Pancreas	Carboxypeptidase
Proelastase	Pancreas	Elastase

These proenzymes become active only in the gastrointestinal tract, which ensures they do not digest the cells that synthesize them. If they were produced in active form, they would destroy their own host tissues. Activation is carefully timed and localized to the digestive system (Trevor Palmer, 1985; Tekman & Öner, 1994; Gözükara, 1997; Sterchi & Stöcker, 1999).

Starting from the 1990s, as biotechnology advanced, enzyme research expanded beyond medicine to include many fields particularly aquaculture, where enzymology, genetics, and histology are now central areas of study.

3. Variations on Digestive Enzyme Activities in Marine Fish Larvae Under Aquaculture Conditions

Marine fish, considered valuable aquatic species, are an essential part of the global food system. However, due to overfishing, natural stocks have experienced significant decline, prompting a sharp rise in the cultivation of marine fish through aquaculture (Hilborn et al., 2020). Among Mediterranean aquaculture species, gilthead sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) are extensively cultured, and numerous studies have been conducted on these species.

In recent years, efforts have intensified to cultivate alternative high-value species. With the emergence of alternative species, new species have become the main subjects of these biotechnological fields. This shift has brought about a surge in biotechnological research, particularly focused on the digestive enzyme development during larval stages, as feeding protocols must be tailored to meet the specific metabolic demands of each species. These studies are vital for optimizing nutritional strategies and improving larval survival rates (Diaz et al., 1997; Zambonino Infante & Cahu, 2001).

The alternative species under aquaculture include:

- **Dentex (*Dentex dentex*)**
- **Meagre (*Argyrosomus regius*)**
- **Common Pandora (*Pagellus erythrinus*)**
- **Red Porgy (*Pagrus pagrus*)**
- **Turbot (*Psetta maxima*)**
- **Grouper (*Epinephelus aeneus*)**
- **Pink Dentex (*Dentex gibbosus*)**
- **Blue-spotted Seabream (*Pagrus caeruleostictus*)**
- **Sharpsnout Seabream (*Diplodus puntazzo*)**
- **Redbanded Seabream (*Pagrus auriga*)**

With each passing year, more species are being evaluated as alternative candidates, driven by the demand for diversification in aquaculture. This expansion also increases the need for scientific data to support their culture (Marangos, 1995; Boglione et al., 2003; Papandroulakis et al., 2004). Some species have been identified as candidates for aquaculture, but mass production has not yet begun, and the development of their digestive enzymes has not been studied.

European Sea Bass (*Dicentrarchus labrax*)

In Mediterranean aquaculture, European sea bass is a key species. Studies on its digestive enzyme ontogeny have emphasized the importance of introducing microparticulate feeds at an appropriate developmental stage. It was observed that early introduction (before day 20) of microparticulate diets led to an increase in amylase activity, influenced by the starch content of the diet. However, early weaning negatively affected larval development by inhibiting pancreatic secretory functions, potentially delaying digestive system maturation (Cahu & Zambonino Infante, 1994).

Gilthead Sea Bream (*Sparus aurata*)

Research on this species revealed that during the first 30 days post-hatch, activities of protease, α-amylase, and acid/alkaline phosphatase enzymes increased notably after day 15. Proteases in *S. aurata* were identified as serine-type enzymes. The intake of exogenous feed exerted a clear regulatory effect on enzyme activity (Moyano et al., 1996).

Common Dentex (*Dentex dentex*)

Newly hatched larvae exhibited higher trypsin and chymotrypsin activity compared to amylase and lipase, suggesting a significant role for serine proteases in yolk protein degradation and hatching. After hatching, trypsin and chymotrypsin levels decreased, while lipase activity increased. There was a developmental shift from alkaline to acid proteases, indicating that alkaline enzymes may not be the primary catalysts before stomach gland formation. Lipase activity peaked around 35 days after hatching (DAH) and decreased once live feed was removed, highlighting the species preference for high-protein diets. Other digestive enzymes such as leucine-alanine peptidase, alkaline phosphatase, and aminopeptidase N were detected in early-stage larvae. Maltase activity only emerged after the start of exogenous feeding. Early onset of brush border enzyme activity between 6 and12 DAH correlated with the species' rapid growth potential (Gisbert et al., 2009).

Common Pandora (*Pagellus erythrinus*)

Total proteolytic activity was alkaline from 0 to 17 days after hatching (DAH), but more acidic proteases were present between 24 and 31 DAH, and these became more prevalent than alkaline proteases in the later stages (38–45 DAH). Trypsin, chymotrypsin, elastase, and carboxypeptidase are examples of alkaline proteases that exhibit the highest protease activity, which was determined at pH 8. An efficient digestive system has developed before live prey is consumed, as evidenced by the detection of activity in a variety of enzymes before feeding begins. Age-related increases in enzyme levels could be linked to intestinal epithelium folding and the subsequent growth of the absorptive surface area during larval development (Caruso et al., 2009).

Sharpsnout Seabream (*Diplodus puntazzo*)

Trypsin activity was detected at hatching and increased during larval development, peaking before day 25, after which it began to decline. Pepsin activity started on day 32, coinciding with stomach development, and reached a peak on day 40 before declining again. Amylase appeared on day 2 and rose until day 10, dropped afterwards, but increased again on day 35 when microparticulate feed was introduced. Lipase was first detected on day 4, increased until day 20, then declined, followed by another rise around day 35 due to dietary changes (Suzer et al., 2007a).

White Seabream (*Diplodus sargus*)

From the moment the mouth opened, all digestive enzymes were discovered to be active in the alternative aquaculture candidate, the sparid species *Diplodus sargus*. Their ontogenetic development profiles were found to be strongly impacted by the conversion from live prey to microparticulate meals during weaning, as well as by the development of organelles during metamorphosis, including stomach formation. A good survival rate following the larvae's weaning off live feed was linked to the early and unique development of digestive enzyme activities (Cara et al., 2003).

The Red Porgy (*Pagrus pagrus*)

Activities of trypsin and chymotrypsin were initially observed on day 3, increased marginally until day 25, and then began to decrease. On day 28, pepsin began to develop in the stomach and peaked on day 30. On days two and four, lipase and amylase were found, exhibiting comparable early trends, with lipase activity declining by 30 DAH. Metamorphic processes like stomach development and food changes were associated with these enzyme alterations. The developmental profile of *Pagrus pagrus* was similar to that of other Sparidae species (Süzer et al., 2007b).

Redbanded Seabream (*Pagrus auriga*)

In southern Spain, this fish is highly valued. During the course of larval development, trypsin activity progressively increased until it stabilized at about 40 UF/individual in larvae older than 25 days after hatching (DAH). Although chymotrypsin's initial activity was faster in larvae up to 10 DAH, it demonstrated comparable activity levels in older larvae. Only fish older than 30 DAH showed considerable acid protease activity. During larval development, amylase activity also rose, albeit considerably less than that of proteases. From the start of the first feeding until 40 DAH, esterase activity quadrupled, peaking at about 100 UF/individual (Moyano et al., 2005).

Blackspot Seabream (*Pagellus bogaraveo*)

This species, with potential for European aquaculture diversification, still lacks comprehensive nutritional data. Amylase activity significantly decreased during development, reaching a level 2.7 times lower at 11 DAH than at 7

DAH, and remained stable between days 45 and 55. Trypsin activity was steady until day 21, possibly reflecting feeding patterns. Lipase activity showed a notable increase in later stages. Among all digestive enzymes, lipase and leucine-alanine peptidase showed the most significant increases between days 45 and 55. These findings link enzyme activity closely with organogenesis and shifts in dietary sources during development (Ribeiro et al., 2008).

Red Drum (*Sciaenops ocellatus*)

Trypsin, amylase, and lipase enzyme ontogenetic development in *Sciaenops ocellatus* larvae showed that their activity started as soon as the mouth opened, peaked on day three, and then progressively decreased over the next few days. Additionally, it was discovered that larvae fed live prey had lower digestive enzyme activity than those fed microparticulate diets (Lazo et al., 2000).

Meagre (*Argyrosomus regius*)

The larvae of *Argyrosomus regius* had a well-developed exocrine pancreas at the start of exogenous feeding, according to histological and enzymatic investigations. They also produced vital pancreatic enzymes, including as lipase and alkaline proteases, which were activated by bile salts. These enzymes were shown to play a central role in food digestion. The major shift in enzyme profiles occurred between 20 and 25 days after hatching (DAH). This period coincided with yolk sac resorption and a complete transition to exogenous feeding. Pepsin activity, an indicator of acidic digestion, was not detected until day 31. The onset of notochord flexion and a progressive decline in alkaline protease and leucine-alanine peptidase activity signalled a shift in the digestive modality from primarily alkaline to the initiation of gastric digestion.

Importantly, pepsin activity appeared only after gastric glands became morphologically visible, cautioning against relying solely on histological indicators for determining digestive capacity. Morphology alone may not reflect functional readiness. The functional development of the digestive system based on alkaline and acidic protease activities is a well-conserved process, primarily driven by body size, rather than larval age or environmental conditions. Therefore, it is recommended to consider morphometric and developmental indicators (e.g., length, stage) alongside chronological age (DAH) when comparing larvae across different studies (Solovyev et al., 2016).

Recent studies on flatfish have increasingly focused on enzyme activity, particularly in alternative species.

American Plaice (*Pseudopleuronectes americanus*) & Yellowtail (*Seriola* spp.)

Activities of alkaline phosphatase, dipeptidyl peptidase IV, aminopeptidase N, and esterase were seen in larvae of *Pseudopleuronectes americanus* and *Seriola sp*. as early as the third day after hatching, and they increased in tandem with morphological development. Furthermore, under starving conditions, yellowtail larvae showed a decrease in aminopeptidase M and esterase activities, but starved winter flounder larvae showed no enzyme activity. (Baglole et al., 1998).

Senegal Sole (*Solea senegalensis*)

Marked changes in pancreatic and intestinal enzyme activities occurred at the early larval phase and the end of metamorphosis. Acid proteases accounted for 10% of total protease activity at day 9, increasing to 75% by day 33. Lipase peaked between days 6 and 10 and again post-metamorphosis, likely reflecting lipid utilisation. Alkaline phosphatase decreased between days 5 and 20, then sharply increased due to enterocyte development in the intestinal lining (Martinez et al., 1999).

Turbot (*Scophthalmus maximus*)

Trypsin peaked at 17 DAH and declined by day 31. Amylase emerged by day 4, peaked at day 19, and declined by day 39. This suggests that molecular components are destabilized to a low level in formulated diets. Pepsin appeared on day 9, increased until day 34, then stabilized. Enzymes associated with the brush border membrane (BBM) such as leucine-alanine peptidase, alkaline phosphatase, and leucine aminopeptidase N were present in newly hatched larvae. BBM enzymes increased markedly until day 23, dropped by day 50, then gradually rose again. By day 38, BBM activity accounted for 81% of total enzyme activity, indicating gut maturation (Tong et al., 2012).

4. Conclusion

Understanding the ontogeny of digestive enzyme activity and its day-to-day variations is critical for enhancing larval quality and improving survival rates in larval rearing. One of the biggest challenges in larval production is the complexity and cost of live feed production. This has driven producers toward using microparticulate diets, which are more scalable and cost-effective. The timing of microparticulate feed introduction must align with the developmental stage of digestive enzyme systems. Introducing artificial diets too early may disrupt enzyme maturation, while being too late may limit growth potential. Feeding strategies must be species-specific, reflecting the natural dietary habits and digestive physiology of each fish. Accurate understanding of enzyme activity profiles allows for the development of scientifically validated and efficient feeding protocols, tailored through biotechnological tools. Thus, the integration of enzymology into aquaculture practices contributes significantly to more sustainable, scientifically grounded, and high-quality fish production systems.

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Bölüm 4

Geçmişten Günümüze Bafa Gölü ve Çevre Sorunları

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Tarih boyunca insanoğlu su ve gıda kaynaklarına kolay erişim, savunma gibi nedenlerle sulak alanlara yakın alanlara yerleşmeyi tercih etmişlerdir. Arkeolojik bulgulara göre Neolitik dönem yerleşim yerlerinin çoğunluğu sulak alanlara yakın konumdadır (Mitsch ve Gosselink, 2015).

Türkiye'nin de taraf olduğu 1971 yılında kabul edilen "sulak alanların korunması sözleşmesi" olarak da bilinen **Ramsar Sözleşmesi**'ne göre sulak alanlar, ***doğal ya da yapay, devamlı ya da geçici, suları durgun ya da akıntılı, tatlı, acı ya da tuzlu; denizlerin gelgit hareketinin çekilme devresinde derinliği altı metreyi geçmeyen sular ile bataklık, sazlık ve turbalık alanlar*** şeklinde tanımlanmaktadır.

Dünyadaki türlerin neredeyse %40'ını barındıran sulak alanlar, doğanın doğal su filtreleri/böbrekleri olarak işlev gören hayati ekosistemlerdir. Zengin biyolojik çeşitliliği ile sulak alanlar, karbon yutakları olarak iklim değişikliğiyle mücadelede olumlu katkılar sunması, su kalitesini iyileştirmesi, faydalanıcılarına ekonomik ve sosyal refah sağlaması gibi geniş bir yelpazede önemli ekosistem hizmetleri sunmaktadır (Kundu vd., 2024, Mitsch vd., 2015).

Bafa Gölü

Çamiçi Gölü olarak da bilinen Bafa Gölü, önceleri Ege Denizi'nin bir koyu iken zamanla Büyük Menderes Nehri'nin taşıdığı alüvyonlarla denizle olan bağlantısı kesilerek doğal bir set gölü haline dönüşmüştür. Türkiye'nin Güney Batısında, Büyük Menderes Deltası'nın Güney Doğusunda, Miletus antik kentinin yaklaşık 10 km doğusunda, Söke-Milas karayolunun doğusunda yer alan göl, Aydın ve Muğla il sınırları içerisindedir (şekil 1). A sınıfı sulak alan kategorisine giren Gölün yüzey alanı yaklaşık 67 km^2, denizden yüksekliği 10

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m ve maksimum derinliği 25 metreye kadar ulaşmaktadır. Büyük ölçüde Büyük Menderes Nehri ile beslenen Göle yağışın bol olduğu zamanlarda Beşparmak Dağları'ndan dökülen küçük derelerle de su taşınımı olmaktadır. 1989 yılında doğal sit alanı olan göl, 1994 yılında ulusal tabiat parkı ilan edilmiş olup uluslararası önemli kuş alanları listesine dahildir. Tipik Akdeniz ikliminin hakim olduğu Bafa Gölü ve çevresinde kış mevsimi ılıman ve yağışlı, yaz mevsimi ise kurak ve sıcak geçmektedir (Cirik ve Cirik, 1995; Davraz ve Yıldız, 2023; Knipping vd., 2008; Müllenhoff vd., 2004; Sarı vd., 1999; Şenyürek vd., 2006).

Şekil 1. Bafa Gölü (Google Earth'ten).

Bafa Gölü Havzasında Biyoçeşitlilik

Büyük Menderes Havzası içerisinde yer alan Bafa Gölü Havzası zengin bir biyoçeşitliliğe sahiptir.

Bafa Gölü Havzası Faunası

2012 yılında Bafa Gölü'nden toplanan makrobentik omurgasız örneklerinin incelendiği araştırmada en baskın grubun %39 baskınlıkla Bivalvia (34300 birey) olduğu, bu grubu %32 baskınlıkla Gastropoda (28858 birey), %17 baskınlıkla Polychaeta (14925 birey) ve %8 baskınlıkla Chironomidae (6941 birey) üyelerin takip ettiği ortaya konulmuştur (Hepsöğütlü, 2012). Bafa Gölü'nde makrobentik omurgasızların belirlendiği bir diğer çalışmada Polycheata sınıfı üyesi iki tür (*Nereis diversicolor* ve *Ficopomatus enigmaticus*) Bivalvia sınıfından iki tür (*Cerastordema edule* ve *Mytilaster marioni*), Gastropoda sınıfından üç tür (*Bithynia tentaculata*, *Potamopgyrus antipodarum* ve *Ecrobia ventrosa*), Crustacea alt şubesinden beş tür (*Gammarus* sp., *Gammarus aequicauda*, *Palaemonetes antennarius*, *Sphaeroma serratum* ve *Balanus* sp.), Arachnida sınıfından bir tür (*Argyroneta aquatica*) ve Insecta sınıfından dört tür (*Platycnemis* sp., *Pyrrhosoma* sp., *Hydrocahara* sp. ve *Chironomus* sp.) bulunmuştur (Akzıypak, 2015).

2001 yılında yapılan bir araştırmada Bafa Gölü'nde 20 balık türünün varlığı saptanmıştır. Bu türler, *Anguilla anguilla*, *Cyprinus carpio*, *Acanthobrama mirabilis* (Endemik), *Chondrostoma meandrense*, *Barbus capito pectoralis*, *Silurus glanis*, *Syngnathus abaster*, *Aphanius fasciatus*, *Gambusia holbrooki*, *Atherina boyeri*, *Dicentrarchus labrax*, *Diplodus sargus*, *Lisa ramada*, *Mugil cephalus*, *Chelon labrosus*, *Salaria pavo*, *S. fluviatilis*, *Gobius niger*, *Knipowitschia caucasica* ve *Pomatoschistus marmoratus* türleridir (Kuru vd., 2001). Bu türlerden sivrisinek balığı (*Gambusia holbrooki*) sonradan göle bırakılmıştır. 2015 yılında yapılan bir diğer çalışmada Gölde yaşamını süren 15 balık türü belirlenmiştir (Demir, 2015). Bu türler *Anguilla anguilla*, *Aphanius fasciatus*, *Atherina boyeri*, *Carassius gibelio*, *Chondrostomata meandrense*, *Chelon labrosus*, *Cyprinus carpio*, *Dicentrarchus labrax*, *Gambusia affinis*, *Knipowitschia caucasica*, *Lepomis gibbosus*, *Liza ramada*, *Mugil cephalus*, *Sparus aurata* ve *Sygnathus abester* türleridir. 2001 ve 2015 yıllarındaki iki çalışma karşılaştırıldığında endemik bir tür olan *Acanthobrama mirabilis* ile *Barbus capito pectoralis*, *Silurus glanis*, *Diplodus sargus*, *Salaria pavo*, *S. fluviatilis*, *Gobius niger* ve *Pomatoschistus marmoratus* türlerinin 2015 yılında yapılan çalışmada tespit edilmediği, *Gambusia holbrooki* türü yerine *G. affinis* türünün belirlendiği ve 2001 yılındaki çalışmadan farklı olarak da *Lepomis gibbosus* ile *Sparus aurata* türlerinin gölde saptandığı sonucu çıkarılabilir.

Göl ve çevresinde yapılan kuş gözlemlerinde 13 türün (mahmuzlu kız kuşu – *Vanellus spinosus*, bataklık kırlangıcı - *Glareola pratincola*, ak kuyruklu kartal - *Haliaeetus albicilla*, küçük batağan - *Tachybaptus ruficollis*, bahri - *Podiceps cristatus*, kara boyunlu batağan - *Podiceps nigricollis*, karabatak - *Phalacrocorax carbo*, küçük karabatak *Phalacrocorax pygmeus*, tepeli pelikan - *Pelecanus crispus*, boz ördek - *Anas strepera*, elmabaş patka - *Aythya ferina*, sakarmeke - *Fulica atra*, su kuşu) üreme veya kışlama amacıyla alanı ziyaret ettiği belirlenmiştir (Kılıç ve Eken, 2004). 2011 Temmuz ve 2012 Haziran ayları arasını kapsayan Atalay (2012) tarafından gerçekleştirilen bir araştırmada barınma, beslenme ve üreme amacıyla Bafa Gölü'nü tercih eden 64'ü su kuşu, 12'si yırtıcı kuş ve 66'sı ötücü kuş olmak üzere toplam 142 kuş türü gözlemlenmiştir. Bu 142 kuş türünden alanda üreyen bazı kuş türleri, küçük batağan - *Tachybaptus ruficollis*, bahri - *Podiceps cristatus*, karaboyunlu batağan - *Podiceps nigricollis*, karabatak - *Phalacrocorax carbo*, küçük balaban

- *Ixobrychus minutus*, alaca balıkçık - *Ardeola ralloides*, sığır balıkçılı - *Bubulcus ibis*, küçük ak balıkçıl - *Egretta garzetta*, gri balıkçıl - *Ardea cinerea*, erguvani balıkçıl - *Ardea purpurea*, leylek - *Ciconia ciconia*, angıt - *Tadorna ferruginea*, kerkenez - *Falco tinnunculus*, kınalı keklik - *Alectoris chukar*, su tavuğu - *Gallinula chloropus*, sakar meke - *Fulica atra*, uzunbacak - *Himantopus himantopus*, sumru - *Sterna hirundo*, kumru - *Streptopelia decaocto*, üveyik - *Streptopelia turtur*, tepeli guguk - *Clamator glandarius*, arıkuşu - *Merops apiaster*, ibibik - *Upupa epops*, karatavuk - *Turdus merula* olup tam tür listesi Atalay (2012)'de verilmiştir.

Bafa Gölü ve yakınındaki İlbir Dağı'nın herpetofaunası Karakulak (1998) tarafından incelenmiş ve Anura takımından dört kuyruksuz kurbağa türü (*Bufo bufo*, *Bufo viridis*, *Hyla arborea* ve *Rana ridibunda*), Testudines takımından iki kaplumbağa türü (çizgili kaplumbağa - *Mauremys caspica* ve mahmuzlu Akdeniz kaplumbağası - *Testudo graeca*), Squamata takımından on kertenkele ve keler türü (*Cyrtopodion kotschyi*, *Hemidactylus turcicus*, *Laudakia stellio*, *Ophisaurus apodus*, *Lacerta danfordi*, *Lacerta trilineata*, *Ophisops elegans*, *Ablepharus kitaibeli*, *Mabuya aurata* ve *Blanus strauchi*) ile yılanları kapsayan Ophidia alt takımından on yılan türü (*Typhlops vermicularis*, *Eryx jaculus*, *Coluber jugularis*, *Coluber najadum*, *Eirenis modestus*, *Elaphe quatuorlineata*, *Natrix natrix*, *Natrix tessellata*, *Telescopus fallax* ve *Vipera xanthina*) belirlenmiştir.

Ayrıca, göl çevresinde vaşak, çakal, tilki, ayı, kaya sansarı, porsuk, oklu kirpi türlerini de kapsayan doğal bir yaşam söz konusudur (Tomay, 2020).

Bafa Gölü Havzası Florası

Havzadaki Beşparmak Dağları'nda *Pinus brutia* (kızılçam) türü geniş bir alanda yayılış göstermektedir. İklim şartlarının uygun olduğu bazı bölgelerde *Pinus pinea* (fıstık çamı) ormanları bulunmaktadır. Dağın zirvesine doğru ise *Pinus nigra* (karaçam) ile *Juniperus oxycedrus* (katran ardıcı) türleri gözlenmektedir. Makilik alanlarda *Olea europaea* (zeytin) ve meşe türleri (*Quercus coccifera*, *Q. pubescens* ve *Q. cerris*) bulunmaktadır. Kandak vadisinde sığla ağacı (*Liquidamber orientalis*) toplulukları yer almaktadır. Bafa Gölü'nün çevresinde bazı laden türleri (*Cistus creticus* ve *C. salvifolius*), kekik türleri (*Thymus* spp.), karabaş (*Lavandula stoechas*), abdestbozan (*Sarcopoterium spinosum*) ve pürene (*Erica manipuliflora*) rastlanılmaktadır. Makilik, garig ve ormanlık alanlarda çeşitli otsu, çiçekli/kokulu ruderal ve geofit bitkiler yaşamaktadır. Dere kenarlarında *Nerius oleander* (zakkum), *Populus alba* (kavak), *Salix alba* (söğüt), *Platanus orientalis* (çınar), *Vitex* *agnus-castus* (hayıt), *Alnus glutinosa* (kızılağaç) gibi türler görülmektedir (Ürker, 2015). Bafa Gölü'nün çevresinde dikenli saz (*Juncus acutus*) ve kamış (*Phragmites australis*) bitkilerine de rastlanılmaktadır (Sel, 2018).

Ayrıca bir yeni kırmızı alg türü olan *Polysiphonia sukatarii* sp. nov. ile kırmızı alg *Lophosiphonia obscura* türü 2021 yılında kayıtlara geçmiştir (Diaz-Tapia vd., 2021).

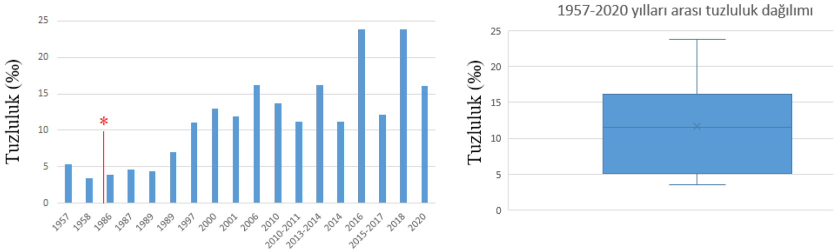
Bafa Gölü'nün Çevre Sorunları

Günümüzde tüm su kütleleri gibi göller de evsel, tarımsal ve endüstriyel atıkların baskısı altındadırlar. Özellikle sulak alanların kurumaya başladığı son yıllarda mevcut sucul ekosistemlerin korunması doğal yaşamın sürdürülebilirliği için kritik derecede önemlidir.

Tuzluluk Yönünden Durum

Bafa Gölü su kolonundaki artan tuzluluğa ilk defa dikkat çeken Sarı vd. (1999) olmuştur. Araştırıcılar göldeki tuzluluğun ‰6 seviyesinden iki kattan fazla artışla ‰13'lere kadar yükseldiğine dikkat çekmişlerdir. Bu durumun göldeki yaşamı etkilediğini stenohalin balık türlerin ekosistemden uzaklaştığı, *Gobius niger* ve *Sygnathus abester* gibi örihalin türlerin göl ekosistemine dahil olduğunu belirtmişlerdir.

Gölde yapılan çalışmalar incelendiğinde tuzluluktaki değişim çok net bir şekilde görülmektedir. Balık ve Ustaoğlu (1989) tarafından yayınlanan bir çalışmada tuzluluğun ‰4,2-4,5 aralığında olduğu kayda geçmektedir. Daha sonra yapılan çalışmalarda en yüksek tuzluluk miktarı ‰23,8 ile Kızılkaya vd. (2016) ile Kurtul vd. (2023) tarafından belirlenmiştir (şekil 2).



Şekil 2. Bafa Gölü'ndeki yıllara göre tuzluluk değişimleri (Kaynaklar: Turgutcan, 1957, Artüz, 1958, Sarı, 1988, Balık ve Ustaoğlu, 1989, Cirik vd., 1989, Sarı vd., 1999, Sarı vd., 2001, Öztürk vd., 2002, Altınsaçlı, 2014, Demir, 2007, Yabanlı vd., 2011, Koçak vd., 2017, Hepsöğütlü, 2012, Yılgör, 2012, Sasi vd., 2017, Kızılkaya vd., 2016, Yozukmaz, 2017, Sukatar vd., 2021a, Kurtul vd., 2023, Tomay, 2020, *1985 yılında sedde yapılmıştır.).

Gölün tuzluluğunun ‰4’lü seviyelerinden ‰20’li seviyelerine dramatik artışın temel nedenleri incelendiğinde ilk olarak karşımıza 1985 yılında Devlet Su İşleri tarafından göl ile Büyük Menderes Nehri arasına yapılan 6 metre yüksekliğinde ve 6 km uzunluğunda sedde çıkmaktadır (şekil 3). Bu seddeden sonra göle tatlı su girişi azalmış ve gölün su seviyesi azalmıştır (Tosunoğlu vd., 2015, Çoban ve Göktuğ, 2023).

Şekil 3. Bafa Gölü ile Büyük Menderes Nehri arasındaki sedde (Tosunoğlu vd., 2015).

Ayrıca Bafa Gölü kıyısında yerleşik olan yavru balık yetiştirme tesislerinin atık sularının da tuzluluk oranı (39.000 mmhos cm^{-1}) göle göre yüksektir (Koç, 2008).

Yağışlardaki azalma ile buharlaşmadaki artış gölün tuzluluk seviyesindeki artışın bir başka nedenidir. Koç ve İrdem (2007)’e göre ülke genelinde normal ve orta şiddetli yağışlarda bir azalma eğilimi görülmektedir. Türkiye, küresel ısınmadan etkilenen riskli coğrafik bölgelerdendir (Koç ve İrdem, 2007). Bu nedenle mevcut su kaynaklarımızın korunması yönünde adımlar atılması zorunludur. Bafa Gölü’nün su yüzey alanının incelendiği bir çalışmada, 2015-2022 yılları arasında, gölün su alanında kayda değer bir değişikliğin olmadığı belirtilmektedir (Atiz vd., 2023). Ancak, Wang vd. (2018)’e göre bu yüzyılın sonunda yani 2100 yılında, küresel ortalama yıllık göl buharlaşmasının %16 oranında artması öngörülmektedir.

Şekil 4’de Bafa Gölü Kapıkırı mevkiinde su çekilmesi nedeni ile karaya oturmuş bir kayık görülmektedir.

Şekil 4. Bafa Gölü Kapıkırı mevkii (orijinal).

Alg Patlaması Sorunu

Ötrofikasyon sucul ekosistemlerin dışardan gelen azot ve fosfor gibi besin maddelerince zenginleşmesi süreci olarak tanımlanmaktadır. Mavi-yeşil ve/veya yeşil alglerin çoğalmasıyla karakterize edilen ötrofikasyon, göllerdeki fiziksel, biyolojik ve kimyasal süreçleri etkileyen başlıca çevre sorunları arasında yer almaktadır. Nutrientlerin artması ile birlikte sucul ekosistemde aşırı alg ve sucul makrofit büyümesi gözlenir (O'Sullivan, 1994, Smol, 2009, Singh ve Rao, 2024, Kacikoc vd., 2025). Artan algal büyümeye bağlı askıda katı madde miktarındaki artış ile birlikte suyun berraklığı azalmakta ve rengi değişmektedir. Ölen organizmalar dipte birikmesiyle organik madde ayrışasına bağlı çözünmüş oksijen seviyesi azalmakta, karbondioksit konsantrasyonu artmakta ve hidrojen sülfür ortaya çıkmaktadır (Chislock vd., 2013, Dorgham, 2013). Ötrofikasyon doğal bir süreç olsa da domestik atıklar, gıda işleme atıkları, azot ve fosfor içerikli gübreler gibi antropojenik etkiler bu süreci hızlandırmaktadır.

Göl su kolonunda ışık geçirgenliğinin azalması, koku ve renk bozulması, çözünmüş oksijen seviyesinin düşmesi, bazı sucul organizmaların ölümü, biyoçeşitlilik kaybı ötrofikasyonun ekolojik etkileri arasındadır (Khan ve Ansari, 2005).

Bafa Gölü'nde de uzun yıllardır ötrofikasyon sorunu yaşanmakta ve buna bağlı sucul organizma ölümleri görülmektedir. 1996 yılında gümüş balığı ve deniz iğnesi ölümlerinin, 2006 yılında ise gümüş balığı, yılan balığı, deniz iğnesi ve karides ölümlerinin gözlemlendiği, gölde rahatsız edici kötü koku ile su yüzeyinde film tabakası varlığı raporlanmıştır (Yabanlı vd., 2011, Şaşı ve Yabanlı, 2015). Yilmaz ve Koç (2014) 2009-2010 yılları dahilinde bir yıllık araştırmalarında gölde plankton büyümesinin çok yüksek olduğunu ifade etmişlerdir. 2010 yılında Bafa Gölü suyunda algal patlamaya neden olan ve hepatotoksik peptit nodularin üreten bir Cyanobacter türü olan *Nodularia spumigena* belirlenmiştir (Kızılkaya vd., 2016). 2010-2011 yıllarını kapsayan periyotta Gölün batı kısmının toplam fosfor yönünden hipertrofik olduğu yapılan bir araştırma ile saptanmıştır (Kocak vd., 2017). Gölde yapılan, 2015-2017 yılları arasını kapsayan bir diğer çalışmada da Carlson Trofik Durum indeksi yönünden elde edilen toplam fosfor değerlerine (1.04-1.92 mg/L) göre hipertrofik durum tespit edilmiş olup seki diski derinliği verilerine (0,50-3,60 m) göre ötrofik durum, klorofil a sonuçlarına (6,00-82,8 µg/L) göre de mezotrofikten hipertrofik duruma kadar değişen trofik statü belirlenmiştir (Sukatar vd., 2021b).

Büyük Menderes Nehri'nden Bafa Gölü'ne yaklaşık 64 ton/yıl TN ile 6,5 ton/yıl TP taşınmaktadır (Kacikoc vd., 2025). Bu da alg patlaması için uygun zemini oluşturmaktadır.

Bafa Gölü'ndeki alg patlamaları ile ilgili görseller (şekil 5-6) ile Serçin'de balıkçı tekneleri civarında akuatik makrofit yoğunluğu (şekil 7) görülmektedir.

Şekil 5. Bafa Gölü Kapıkırı mevkiinde göl yüzeyinde alg topluluklarının oluşturduğu film tabakası (orijinal).

Şekil 6. Bafa Gölü Çayı üzerindeki regülatör civarında suda alg patlaması (orijinal).

Şekil 7. Bafa Gölü Serçin mevkiinde akuatik makrofitler (orijinal).

Sediment Kirliliğinin Değerlendirmesi

Yilgör vd. (2012), 2010 yılında Bafa Gölü'nden aldıkları yüzey sedimentlerinde belirledikleri elementleri konsantrasyonlarına göre Fe > Mn > Ni > Cr > Zn > Cu > Pb > Hg şeklinde sıralamışlardır. Araştırıcılar, zenginleşme faktörü (EF) sonuçlarına göre Pb, Zn ve Hg yönünden insan kaynaklı kirlilik, kontaminasyon faktörü (CF) açısından Hg için orta-yüksek kontaminasyon ve jeo-birikim indeksine (Igeo) göre de Hg yönünden hafif kirlenmenin olduğunu ortaya koymuşlardır. 2010-2011 yılları arası yapılan bir çalışmada 4 örnekleme döneminde toplanan sedimentlerde belirlenen ağır metal konsantrasyon sıralaması Cr > Pb > Zn > Cu > Cd > Hg şeklindedir (Aydin-Onen vd., 2015). 2012 yılında örneklenen sediment örneklerinde Ni seviyesi, etki aralığı medyan sınırının üzerinde tespit edilmiş olup sedimentte Ni birikiminin su kalitesini olumsuz etkileyebileceği bildirilmektedir (Manav vd., 2016). 2013-2014 yıllarında yapılan bir başka araştırmada, 12 aylık sediment örneklemesi yapılmıştır. Araştırıcılar, elementlerin konsantrasyonlarına göre sıralanmasını Fe > Al > Mn > Ni > Cr > Zn > Pb > Co > Cd şeklinde bulmuş olup EF değerlendirmesinde gölün Al ve Pb birikimi yönünden risk altında, CF yönünden gölün ağır metal kirliliği açısından baskı altında, kirlilik yük indeksi (PLI) verilerine göre kirlilik tehlikesi etkisinde olduğu belirlenmiştir. Aynı çalışmada potansiyel ekolojik risk değerlendirmesi (PERI) hesaplamalarına göre bazı istasyonlarda orta derecede ağır metal kirliliği riskinin varlığı rapor edilmiştir (Yozukmaz ve Yabanlı, 2023). 2015 yılında 5 istasyondan sediment örneklerinin ağır metaller yönünden incelendiği bir çalışmada bir istasyonda Cr ve Ni konsantrasyonlarının limit değerleri aştığı ifade edilmiştir (Sel, 2018). 2015-2016 yılları içerisinde, Bafa Gölü'nden elde edilen sığ sediment örneklerinde ağır metallerin durumu araştırılmış ve ortalama konsantrasyonlarına göre ağır metallerin Fe > Mn > Ni > Cr > Zn > Cu > Co > Pb > Cd şeklinde sıralandığı kaydedilmiştir. Aynı çalışmada Cr, Cu ve Ni elementleri yönünden Bafa Gölü ekosisteminin tehdit altında olduğunun altı çizilmiştir (Algül ve Beyhan, 2020).

Yapılan bir çalışmada 1960'lı yıllarda Büyük Menderes Nehri etrafında sanayileşmenin artmasının ve tarımsal değişimin etkilerinin Göl sedimentinde ağır metal birikimine yansıdığı belirtilmektedir (Manav, 2023).

Bafa Gölü sedimentinde pestisit ve poliklorlu bifenil (PCB) varlığı yönünden yapılan araştırmada, göl yaşamını ters yönde etkilemeyecek derecede düşük konsantrasyonlarda dikloro-difenil-trikloroetan (DDT) türevlerinin varlığı saptanmış, toplam PCB yönünden ise göl kıyısındaki endüstriyel tesisler civarında düşük değerli etki seviyesini geçen konsantrasyonlar belirlenmiş olup diğer istasyonlarda göl yaşamı için risk olmadığı ortaya konulmuştur (Pazı vd., 2013).

Fekal Koliform ve Fekal Streptekok Açısından Durum

Gölün su kolonunda yapılan yayınlanmış mikrobiyolojik çalışma sayısı oldukça sınırlıdır. Yaz mevsiminde 17 istasyondan alınan su örneklerinin incelendiği bir çalışmada üç istasyonda yüksek konsantrasyonlarda fekal koliform saptanmış olup bu durumun rekreasyonel amaçlı faaliyetlerde bulunanlar insanlar için fekal kontaminasyonlu su kaynaklı ishal, dizanteri, tifo ve cilt, kulak, burun vb. enfeksiyonları yönünden risk oluşturduğu ifade edilmektedir (Kacar, 2015).

Biyolojik Örneklerde Kontaminantlar

Sel (2018) tarafından Göl kenarında yayılış gösteren *Juncus acutus* ile *Phragmites australis* bitkilerinin Cu, Cd, Mn ve Zn elementlerini etkili bir biçimde biyoakümüle ettiği saptanmıştır. Gölden elde edilen *Dicentrarchus labrax* (levrek) balıklarının kas dokularında belirlenen ağır metallerin (Al, Cr, Ni, Cu, As, Cd, Hg, Pb) ulusal ve uluslararası tüketimle ilgili sınır değerleri aşmadığı araştırıcılar tarafından belirtilmiştir (Yabanlı vd., 2013). Göldeki *Mugil cephalus* (kefal) balıklarında ağır metal (Cu, Zn, Fe, Cd, Pb) varlığının araştırıldığı bir araştırmada çalışılan kas dokusu örneklerinin %16'sının Cd yönünden, %68'inin de Pb yönünden limit değerlerin üzerinde olduğu bilgisi verilmiştir (Öner ve Metli, 2021). Bafa Gölü'nden yakalanan *Dicentrarchus labrax* (levrek), *Liza ramada* (kefal) ve *Anguilla anguilla* (yılan balığı) örneklerinde ağır metal (Zn, Cd, Pb) varlığı ile ilgili bir araştırma sonuçlarına göre tüketimle ilgili yasal değerlerin aşılmadığı ortaya konmuştur (Manav vd., 2016).

Bafa Gölü ile İlgili Öneriler

Gölde evsel, endüstriyel ve tarımsal kirleticiler yönünden belirlenecek kritik noktalarda periyodik izleme programı oluşturulması ve biyoçeşitliliğin takip edilmesi gerekmektedir. Bafa Gölü'ne ana su girişi Büyük Menderes Nehri aracılığı ile olmaktadır. Okur vd. (2011), Büyük Menderes Nehri'nde yüksek miktarda azot ve fosfor içerdiğini, deşarj edilen evsel ve endüstriyel atıklarının zamanla ekosistem için kritik düzeye geleceğini ve acil önlem alınması gerektiği yönünde uyarılarda bulunmuştur. Yine Yilgör (2009) Büyük Menderes Nehri ve Deltasında ağır metal kirliliğinin başladığını ifade etmiştir. Dolayısıyla Büyük Menderes Nehri, Bafa Gölü gibi kirleticiler ve biyoçeşitlilik yönünden üniversitelerin de desteği alınarak sıkı bir şekilde takip edilmeli, 25.000 km^2lik bir alana sahip olan Büyük Menderes Havzası'ndaki sanayi tesisleri ile belediyelerin arıtma tesislerinin faal ve etkili bir şekilde işletilmeleri sağlanmalı, tarım arazilerinde kontrollü gübre ve zirai ilaç kullanımı yönünden çiftçileri bilinçlendirici adımlar atılmalıdır. Gerek Bafa Gölü'nde gerekse de Büyük Menderes Nehri'nde kirletici ve biyolojik çeşitlilik izleme programlarının sonuçları eş zamanlı olarak herkesin erişebileceği bir web portalında paylaşılmalıdır. Her üretim faaliyetinde atık ortaya çıkmaktadır. Oluşan atıkların kontrollü ve etkili bir biçimde doğaya karışmadan bertaraf edilmesi oldukça önemlidir. Büyük Menderes Havzasını kapsayan tüm paydaşları içeren topluluklara yönelik çevre kirliliğinin etkileri, çevre koruma, biyoçeşitliliğin önemi ile ilgili eğitimleri de kapsayan etkinlikler düzenlenmelidir. Bu etkinlikler geleneksel hale dönüştürülmelidir. Bafa Gölü'ndeki biyolojik zenginlikleri gösteren bilgilendirici panolar oluşturulup gölde halkın yoğun olduğu yerlere yerleştirilmelidir. Unutmamalıdır ki doğal kaynaklarımızın korunup daha iyi bir şekilde gelecek nesillere aktarılması hepimizin sorumluluğundadır.

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Chapter 5

Heavy Metal Pollution in Freshwater: Ecotoxicological Risks and Current Monitoring Approaches

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1. Introduction

Although freshwater ecosystems are indispensable resources for biodiversity and human life, they are currently under serious threat due to increasing environmental pressures. Heavy metals are the most prominent of these threats due to their persistent, high bioaccumulation potential, and toxic effects (Edo et al., 2024). Heavy metal pollution not only disrupts ecosystem functioning but also directly threatens human health through the food chain (Angon et al., 2024). Therefore, the accumulation levels of heavy metals in freshwater, their ecotoxicological effects, and monitoring methods have become intensely debated topics in the literature in recent years (Irfan et al., 2023).

Various approaches have been developed to understand the ecotoxicological dimensions of heavy metal pollution. A comprehensive review by Kanwel et al. (2025) systematically examined environmental and statistical indices used in freshwater ecosystems, making significant contributions to the assessment of heavy metal accumulation in sediments on a global scale. However, it is emphasized that analyses based solely on single measurements are insufficient and that the combined use of multiple indicators provides more reliable results.

Indeed, ALLOUCHE et al. (2024) emphasized the increasing importance of the "broad taxon approach" in ecotoxicology studies, stating that the responses of different species groups to pollution should be evaluated together. This approach allows for a more comprehensive understanding of the multidimensional ecological effects of heavy metals, from the cellular level to the population and community level. Similarly, Ceschin et al. (2021)

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demonstrated that aquatic plants are critical bioindicators in monitoring heavy metal pollution, demonstrating that plant responses to environmental stress factors, in particular, can be used to reliably assess the ecotoxicological status of freshwater ecosystems.

Furthermore, heavy metal pollution is not limited to aquatic systems; it also impacts freshwater through terrestrial inputs. Field research conducted by Kravchenko et al. (2025) around a coal-fired thermal power plant demonstrated that heavy metals accumulated in soils pose serious risks not only to terrestrial ecosystems but also to freshwater ecosystems and human health. Similarly, in their study on the Olt River in Romania, Iordache et al. (2022) examined the accumulation of heavy metals in surface sediments, drawing attention to the persistent effects of this pollution from the past to the present and emphasizing that ecotoxicological risks should be evaluated within the framework of long-term monitoring programs.

The environmental persistence, bioaccumulation, and toxicity of heavy metals necessitate holistic approaches in the assessment of these pollutants. Edo et al. (2024) examined the dynamics of heavy metals in freshwater and marine habitats, demonstrating the need to consider persistence and bioaccumulation processes in environmental risk assessments. This approach demonstrates the need to assess not only current pollution levels but also long-term impacts. A similar integrated perspective was adopted by Chung et al. (2024); the combined use of chemical analyses and ecotoxicity tests allowed for more reliable assessment of heavy metal pollution and the identification of the most critical ecotoxicants. This study also demonstrated that risks can be defined more precisely by calculating predicted no effect concentration (PNEC) values.

Local studies also support this global literature. In the Turkish context, Ustaoğlu (2021) evaluated heavy metal pollution in surface sediments in the Çömlekci Stream in Giresun, emphasizing the importance of using different indices together to determine ecotoxicological risks. These findings demonstrate the inadequacy of national criteria for heavy metals in Turkey and the need to develop assessment tools compatible with international standards.

In recent years, real-time approaches have become prominent in monitoring heavy metal pollution in freshwater. In their study on a neotropical stream in Brazil, de Campos Júnior et al. (2025) integrated chemical analyses of heavy metals with ecotoxicological tests, providing an effective method for managing environmental threats. This approach highlights the importance of assessing pollution not only in the laboratory but also in the field and on an ad hoc basis. Furthermore, Singh et al. (2025) emphasized that heavy metals should also be considered in the context of emerging pollutants, stating that heavy metals, along with pesticides, pharmaceuticals and microplastics, are still one of the most critical environmental threats and the use of innovative monitoring techniques has become inevitable.

2. Heavy Metal Sources and Routes of Entry

Heavy metals enter freshwater primarily through anthropogenic pathways, as well as natural processes (geological weathering and erosion): mining and acid mine drainage (AMD), metalworking/industrial discharges, urban/vehicular runoff, and agricultural inputs are critical sources (Aziz et al., 2023). Atmospheric transport and deposition through precipitation are also important pathways.

The presence of heavy metals in freshwater ecosystems is a multifaceted environmental problem arising from the interaction of both natural and anthropogenic processes. The sources of these pollutants are too diverse to be explained solely by single activities; natural events and anthropogenic interventions occurring at different scales cause the transport of heavy metals to aquatic environments. While geological weathering, erosion, volcanic activity, and surface transport are prominent among natural processes; It is stated that today the dominant effects are caused by anthropogenic factors such as mining, industrial activities, agricultural practices, urban wastewater and atmospheric deposition (Kapoor & Singh, 2021; Edo et al., 2024).

Studies on river ecosystems indicate that multiple anthropogenic sources increase the heavy metal load in freshwaters. Rani et al. (2022) demonstrated that mining, industrial discharges, domestic wastewater, and agricultural inputs play a critical role in metal entry into river systems, with atmospheric transport also contributing to this process. Similarly, Khan et al. (2022) conducted a large-scale assessment of the Indus drainage system in Pakistan, emphasizing that industrial and agricultural sources, as well as domestic waste from residential areas, contribute to heavy metal pollution in freshwaters. Such studies demonstrate that pollution is not limited to localized areas but rather spreads over wider geographic areas due to the hydrodynamic characteristics of drainage basins.

It has been demonstrated that heavy metal input is not limited to point discharges but also occurs through diffuse sources and hydrological processes. Wang et al. (2025) demonstrated that water-land migration during flood events is an overlooked pathway for the transport of heavy metals to agricultural soils. This process demonstrates that heavy metal accumulation in aquatic environments continues through both direct and indirect transport pathways. Similarly, Luo et al. (2021) demonstrated that river-lake connections in the

Yangtze River and its tributary lakes increase the diffusion of heavy metals, and that these connections play a critical role in the large-scale spatial distribution of pollution. These findings demonstrate that hydrological connections and flow dynamics are key factors shaping the spread of pollution in freshwaters.

Another dimension of heavy metal sources is industrial processes. Monib et al. (2024) stated that metal processing, chemical, textile, and energy production activities transport heavy metals to river systems through surface runoff and seepage, in addition to direct discharges. This demonstrates that industrial pollution accumulates in freshwater through both direct and indirect pathways, necessitating management strategies at the basin level. Furthermore, Jayakumar et al. (2021) emphasized that heavy metals accumulated in soils contribute to freshwater pollution through precipitation, surface runoff, and groundwater, demonstrating that soil-water interactions are also important pathways for pollutant transport.

However, heavy metal pollution should be assessed not only at the ecosystem level but also through multiple risk pathways for human health. Gupta and Gupta (2023), in their study of river systems in India, demonstrated that different exposure pathways, such as drinking water, fish consumption, and dermal contact, pose a cumulative risk and that carcinogenic and non-carcinogenic effects can be calculated more precisely with Monte Carlo simulations. Such studies demonstrate that assessing heavy metal sources requires considering not only input pathways but also their impact on human health.

At a global scale, the fate of heavy metals in aquatic systems, their transformation processes, and transport pathways demonstrate that they pose a multifaceted environmental threat. Piwowarska et al. (2024) addressed the migration pathways, chemical transformations, and environmental persistence of heavy metals, emphasizing that industry, agriculture, mining, urban runoff, and atmospheric deposition are the primary global sources. These findings demonstrate that international regulations, such as the European Union Water Framework Directive, are also built upon the need to better define the source and input pathways of heavy metal pollution. Similarly, Edo et al. (2024) revealed that heavy metals persist for a long time in the water-soil-sediment cycle due to their environmental persistence, therefore pollutants continuously enter freshwaters depending not only on the source but also on transport and transformation processes.

At the local level, studies conducted in Turkey demonstrate the importance of heavy metal input pathways in the national context. In his study on the Çömlekci Stream in Giresun, Ustaoğlu (2021) analyzed heavy metal pollution in surface sediments, emphasizing the importance of using different indices together to determine ecotoxicological risks and highlighting the inadequacy of national criteria. These findings demonstrate that the sources of heavy metals in Turkey are both similar to global trends and require more specific management strategies at the regional scale.

4. **Ecotoxicological Risks**

In freshwater ecosystems, heavy metals pose one of the most serious ecotoxicological threats due to their environmental persistence, bioaccumulation tendency, and toxic effects. These metals accumulate in sediments, the water column, and biota, directly affecting both ecosystem functions and human health. Sediments stand out as important reservoirs for heavy metals in particular, becoming a constant source of risk to ecosystem health through the re-release of accumulated pollutants into the water column over time. Iordache et al. (2022) stated that high cadmium (Cd) accumulation in sediments from the Olt River in Romania poses serious risks to aquatic organisms; Ustaoğlu (2021) demonstrated that lead (Pb) and cadmium (Cd) pressures in Çömlekci Stream in Giresun exceed international standards and pose high risk levels through ecotoxicological indices. These findings demonstrate that heavy metal accumulation in sediments is not only an indicator of pollution but also a determinant of acute and chronic effects on the ecosystem.

Hydrological events also directly affect the magnitude of ecotoxicological risks. Lim et al. (2021) showed that heavy metals remobilized after a large-scale flood event in the Pahang River in Malaysia and exceeded critical threshold values in sediments, increasing ecotoxicity. Similarly, Islam et al. (2021) evaluated heavy metal distribution along the Bay of Bengal coast together with physicochemical parameters, demonstrating that environmental conditions (pH, dissolved oxygen, temperature, salinity) can increase or decrease metal toxicity. These findings demonstrate that ecotoxicological risks are a dynamic process that interacts not only with metal concentrations but also with environmental factors.

Spatial differences in the distribution of heavy metals also play a critical role in the assessment of ecotoxicological risks. Singh et al. (2021) studied sediments adjacent to river ecosystems, emphasizing that metals such as zinc (Zn), lead (Pb), and copper (Cu) are concentrated in specific areas, and that these "hot spots" significantly increase ecotoxicological risks. Spatial heterogeneity suggests that risks are not uniformly distributed in freshwater ecosystems, and that certain regions are at higher risk of ecotoxicity.

Biodiversity-level studies reveal the direct effects of heavy metals on aquatic organisms. Tang et al. (2023), in a study conducted on organisms at different trophic levels in the Pearl River estuary in China, showed that metals such as cadmium (Cd), lead (Pb), and mercury (Hg) led to high risk factors, particularly in sensitive species, and that multiple metal exposures increased toxicity through synergistic effects. These findings demonstrate that ecotoxicological risk analyses should evaluate not only individual metals but also metal combinations together.

The ecotoxicological aspects of restoration and management initiatives should not be overlooked. How et al. (2023) determined that heavy metal concentrations decreased in polluted river sediments treated with microbial restoration, but the ecotoxicological risk levels of some metals remained high. This suggests that pollution mitigation methods should be evaluated not only with chemical data but also with toxicity tests and ecosystem responses.

The ecotoxicological risks of heavy metal pollution are also critical for human health. Rao et al. (2025), examining sewage sludge generated from drinking water treatment plants in Ghana, demonstrated that while non-carcinogenic risks are low for children and adults, some elements may pose a potential cancer risk. This study demonstrates that the ecotoxicological effects of heavy metals are not limited to the ecosystem but also pose multidimensional risks to public health.

Finally, risks appear to be shaped not only by metal concentrations but also by source distributions and controlling factors. Islam et al. (2025), in their study using a receptor model in a transboundary river basin, demonstrated that metals such as cadmium (Cd), lead (Pb), and arsenic (As) pose the highest ecotoxicological risks, and that these risks are determined by the interaction of geological structure, hydrological processes, and human activities. This approach demonstrates that ecotoxicological risk assessments in freshwater ecosystems should be considered not only with measured values but also with the sources of pollutants and environmental control factors.

3. Current Monitoring Approaches

Chemical analysis: Atomic absorption assay (AAS) and ICP-MS are the gold standards for the determination of multiple metals at trace levels (APHA, 2017; Standard Methods 3125 ICP-MS). Portable XRF is increasingly validated for rapid screening in sediment and soil (El Mellouki et al., 2025; Li et al., 2025). Biological monitoring: Mussels, fish tissues, and bioindicator enzymes/proteins (e.g., metallothionein, antioxidant enzymes) sensitively reflect metal exposure (Raj et al., 2023; Wang et al., 2025). Bioavailability-based approach: Metal toxicity is sensitive to water chemistry (pH, DOC, hardness, ionic strength). Bioavailability-based EQS applications, including the Biotic Ligand Model (BLM) and EU Guide 38, are used to derive site-specific criteria (EPA, 2007; EC, 2021/Guidance No. 38). GIS/Remote sensing: Although heavy metals are not directly detected, hotspot mapping and temporal trend tracking are possible with proxies such as SPM/turbidity (Xu et al., 2024).

3.1. Monitoring Through Fish

Fish are among the most important bioindicators of heavy metal pollution in freshwater ecosystems. This is because metals can easily bioaccumulate from their dissolved forms in the aquatic environment and persist in fish tissues for long periods. This poses critical risks both in terms of ecotoxicology and food safety.

Sharma et al. (2024) emphasize that heavy metals accumulate in fish tissues and cause toxic effects on reproduction, growth, and behavioral processes, making it important to use fish as biological material in regular monitoring studies. Similarly, Irfan et al. (2023), in their bibliometric review specifically focusing on cadmium, revealed that biomarker-based methods (enzyme activities, oxidative stress parameters, DNA damage indicators) in fish are rapidly spreading globally.

Regional studies also support this importance. Elumalai et al. (2023) showed that high levels of metals such as lead, mercury, and cadmium accumulate in freshwater fish in Southern India, posing a serious risk to both ecosystem health and human consumption. Kovacik et al. (2025), from a broader biological perspective, stated that metal exposure in fish has sublethal effects on immune response, oxidative stress, and enzymatic activity, and therefore, biological response indicators must be considered in monitoring studies.

Burch, (2022), presenting an example from Africa, conducted a study on surface water, sediment, and Nile tilapia from Lake Nasser in Egypt, emphasizing that fish are the bioindicator species that most clearly reflect metal transfer into the food chain. These findings demonstrate that fish are essential biological materials for monitoring not only environmental pollution but also risks directly affecting human health.

3.2. Water and Sediment Monitoring

In addition to fish, water and sediment samples are also critical for understanding heavy metal pollution in freshwater. This is because metals, along with their dissolved forms circulating in the water column, form long-term reservoirs in sediments, posing a persistent risk to the ecosystem.

Stefanidis and Papastergiadou (2024) stated that physical-chemical analyses alone are insufficient in ecological monitoring studies, and that multi-parameter approaches supported by biological indicators are necessary. Furthermore, remote sensing and automated sensor technologies are becoming increasingly important in the real-time monitoring of heavy metal pollution in freshwater.

New methods developed for specific metals are particularly noteworthy. Ali et al. (2022) demonstrated that monitoring different chemical forms of mercury is difficult with classical methods, and therefore, nanotechnology-based sensors, electrochemical detectors, and fluorescence biosensors will become widespread in the future. Similarly, Li et al. (2023) emphasize that functional materials (metal-organic cages, graphene derivatives, polymer sensors) offer high potential in both detection and removal of heavy metal ions, and these approaches should be integrated into portable systems. Regional-scale field studies also demonstrate the importance of water and sediments. Ahmed et al. (2023) reported that metals such as lead, arsenic, and cadmium accumulate at high levels in water and plants in agricultural drainage areas near industrial zones, posing serious public health risks. Monib et al. (2024) examined the transport of industrially sourced heavy metals in river basins and observed particularly high accumulations in sediments, emphasizing the need for basin-scale monitoring programs. Burch, (2022) also demonstrated that sediments are the most important storage area for heavy metal pollution in Lake Nasser. These findings demonstrate that water and sediments reveal not only the current state of pollution but also the long-term accumulation and persistent threats to ecosystem health. Therefore, it is clear that fish, water, and sediments should be evaluated with a holistic approach in heavy metal monitoring studies in freshwater.

4. Sustainable Management and Prevention

Threshold/criteria: WHO drinking water guidelines (e.g., As = 10 µg/L), EU 2013/39/EU and priority substances/EQS, and US EPA national recommended water quality criteria are the primary references (WHO, 2022; EU, 2013; EPA, 2025). In Turkey, the Surface Water Quality Regulation (OG 28483, 30.11.2012; amended 2015, 2016) and the Surface/Groundwater Monitoring Regulation are in force (Ministry of Agriculture and Forestry, 2012/2016; 2023). Technical/operational: Source reduction, advanced wastewater treatment, mine drainage control, stormwater management on impervious surfaces; sediment management (dredging) and ecosystem-based restoration should be considered together (Kalyani & Babu, 2024; Sojka & Jaskuła, 2022).

4.1. Global Threats and Management Approaches to Freshwater Resources

Freshwater resources are strategically important for both ecosystem health and human needs. However, pressures such as increasing population, industrialization, agricultural intensity, and climate change threaten the sustainability of these resources. Bănăduc et al. (2022) emphasize that freshwater plays a critical role not only for drinking and agricultural irrigation, but also for energy production and ecosystem services. According to the researchers, sustainable management requires protecting existing resources, preventing pollution, efficient water use, and expanding secondary resource recovery.

Similarly, Irtyshcheva et al. (2023) directly link the management of freshwater resources to the Sustainable Development Goals (SDGs), stating that ecological, economic, and social dimensions should be addressed in a holistic manner, particularly through environmental protection expenditures, institutional collaborations, and public awareness.

4.2. Regional Case Studies and Public Health Risks

Heavy metal pollution in freshwater ecosystems is often of regional origin and has direct impacts on local public health. Afzaal et al. (2022) revealed that heavy metal levels in freshwater in Pakistan have reached dangerous levels in fish and sediments, posing a serious threat to both the ecosystem and food security.

Zulfiqar et al. (2025) also addressed pollution from agricultural and industrial activities in Pakistan, highlighting the importance of policy interventions for sustainable management. Key recommendations in the study included strict enforcement of environmental regulations, monitoring of industrial discharges, limiting the use of fertilizers and pesticides, and expanding wastewater treatment facilities.

Oyeniran et al. (2021) showed that slaughterhouse wastewater contains high levels of iron and lead, and that direct discharge of these waters causes genetic, hematological, and biochemical deterioration in freshwater fish. Researchers emphasize that pre-treatment practices are essential to prevent such pollution and that this process should be addressed in the context of SDG 6 (clean water and sanitation) and SDG 11 (sustainable cities and communities).

4.3. Environmentally Friendly and Innovative Reduction Methods

Not only control and legislation, but also the development of environmentally friendly technologies are critical for sustainable prevention strategies. Singh et al. (2024) state that adsorption-based methods are effective in removing heavy metal ions from water, and that biosorbents, materials derived from agricultural waste, and green synthetic nanotechnologies, in particular, offer low-cost and ecological solutions. Mukherjee et al. (2021) also stated that methods such as bioremediation, phytoremediation, and microbial treatment offer advantages in terms of environmental adaptation and energy efficiency. These approaches not only enable the removal of pollutants but also enable the long-term preservation of ecosystem health.

4.4. Ecosystem Services and Regulatory Natural Mechanisms

Natural processes also play an important role in reducing heavy metal pollution. Cheng et al. (2021) demonstrated that soils act as a natural barrier to heavy metal fixation, and that this characteristic is critical for protecting freshwater ecosystems. The study emphasized that sustainable soil management is a preventative strategy for long-term water quality protection.

Grant et al. (2022) addressed the stakeholder-focused management of freshwater resources within the framework of Shared Resources Theory. According to this approach, freshwater is not only a resource under the control of states but also an asset under the shared responsibility of local communities, sectors, and individuals. Therefore, governance models based on stakeholder participation serve as a critical catalyst for sustainable management.

4.5. Integrated and Multidisciplinary Approaches

The future of sustainable water management depends on approaches that integrate different disciplines and scales. Izah et al. (2023) propose the "One Health" approach, advocating for the development of ecosystem-based management plans that address human, animal, and environmental health together. The study states that technical monitoring and treatment alone will not be sufficient to control heavy metal pollution; public health policies, agricultural strategies, and social awareness efforts must also be integrated.

5. Conclusion and Future Perspectives

Heavy metal pollution in freshwater ecosystems is a growing global problem in terms of both environmental sustainability and public health. Studies show that the use of fish as bioindicators allows understanding the biological effects of heavy metals, while water and sediment analyses reveal the current status and long-term accumulation processes of pollution (Sharma et al., 2024; Kovacik et al., 2025; Burch, E. 2022). Current monitoring approaches increasingly utilize bioindicator-based measurements, ecotoxicological parameters, and remote sensing systems, in addition to classical chemical analysis methods (Stefanidis & Papastergiadou, 2024; Irfan et al., 2023). Furthermore, nanotechnology-based sensors, functional materials, biosensors, and artificial intelligence-assisted data processing techniques are considered innovations that could lead to a paradigm shift in monitoring heavy metal pollution in the future (Ali et al., 2022; Li et al., 2023). Regional examples reveal varying risks depending on the source and extent of heavy metal pollution in different geographies. While assessments of fish in Southern India highlighted food security risks (Elumalai et al., 2023), a comprehensive environmental assessment of Lake Nasser demonstrated that sediments are a long-term reservoir of pollution (Burch, 2022). Similarly, high risks to human health have been demonstrated in agricultural drainage areas interspersed with industrial zones (Ahmed et al., 2023; Monib et al., 2024).

Consequently, multidisciplinary, holistic, and technologically innovative approaches must be adopted for monitoring heavy metal pollution in freshwaters. The combined evaluation of fish, water, and sediment samples; the integration of biological and chemical indicators; the adaptation of next-generation functional materials to field applications; and the development of artificial intelligence-supported data analysis systems are key requirements for the future of this field. In this context, regular, systematic monitoring, and compliance with international standards are critical to ensure both ecosystem health and public health. Heavy metal pollution in freshwaters is a challenging, multidisciplinary problem due to the complex sediment-water-biota cycles, high persistence, and bioavailability dynamics. The combined use of chemical, biological, and bioavailability-based monitoring tools, the alignment of thresholds/criteria with current science, and basin-based management approaches are critical (WHO, 2022; EPA, 2025; EC Guidance No. 38).

Managing and preventing heavy metal pollution in freshwater ecosystems requires a multidimensional and interdisciplinary approach that is not limited to technical and scientific solutions. Literature findings suggest that global threats need to be identified and strategies developed within the SDG framework (Bănăduc et al., 2022; Irtyshcheva et al., 2023), that public health risks are increasing at the regional level (Afzaal et al., 2022; Zulfiqar et al., 2025; Oyeniran et al., 2021), that environmentally friendly treatment and abatement methods provide sustainable solutions (Singh et al., 2024; Mukherjee et al., 2021), and that preserving natural regulatory processes (Cheng et al., 2021) and stakeholder-focused management models (Grant et al., 2022) are critical for long-term success. Furthermore, it is emphasized that integrated models such as the "One Health" approach (Izah et al., 2023) jointly safeguard human, animal, and environmental health. Consequently, it is imperative that sustainable management and prevention strategies for the protection of freshwater resources are supported not only by scientific-technological solutions, but also by policy interventions, ecosystem services and community participation.

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Chapter 6

Insect Protein in Sustainable Aquaculture Feeds: The Yellow Mealworm Example

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1. INTRODUCTION

With the rapid growth of the world's population, the aquaculture sector has become a pillar of global food security due to its importance in providing affordable, high-quality protein. This increase, projected to reach approximately 10 billion by 2050, poses significant pressure on global food security (FAO, 2018). With this growing population, the demand for animal protein is also increasing significantly, placing aquaculture in a strategic position for sustainable protein production. Since the 1990s, the aquaculture sector has grown by an average of over 5% annually, accounting for approximately half of the world's fish production (Naylor et al., 2021). This rapid development has made the sector one of the most dynamic components of the global food supply.

However, the sector's growth also presents a critical challenge for environmental sustainability: the need for fish feed. Traditionally used fish meal (FM) and fish oil (FO), which have high nutritional value, pose a significant obstacle to sustainability goals by contributing to overfishing and ecological limitations in wild fish stocks (Tacon and Metian, 2008; FAO, 2020). This environmental pressure and limited resource availability are continuously increasing feed costs, as feed accounts for a significant portion of aquaculture production costs, ranging from 40% to 80% (Rana et al., 2009; Alfiko et al., 2022). This is forcing the sector to reduce its reliance on FM and FO and turn to innovative, economical, and environmentally friendly alternative protein sources.

Soybean meal (SBM), an indispensable and widely used plant protein source for fish feed, presents its own nutritional and environmental challenges. Despite its high protein content, soybean meal contains anti-nutritional factors (trypsin inhibitors and saponins) that can cause digestive problems, particularly in

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carnivorous fish species. Furthermore, soybean production conflicts with environmental sustainability goals due to high land use, deforestation, pesticide use, and a high carbon footprint (Rana et al., 2009; Oliva-Teles et al., 2015). Consequently, the reliance on both FM and SBM increases the economic and ecological vulnerability of the aquaculture sector. This dual limitation—resource depletion in fish meal and environmental disadvantages in soybean meal—requires a fundamental change in the composition of fish feeds, forcing the sector to turn to innovative, economical, and environmentally friendly alternative protein sources. Research in the last two decades has focused on microbial proteins (single cell proteins), algae (Spirulina, Schizochytrium *sp.*), animal by-product-derived flours (blood meal, meat-bone meal, feather meal) and especially insect proteins (Henry et al., 2015; CABI, 2023; Behera et al., 2024; EAAP, 2024).

In this context, insect species, particularly black soldier fly (*Hermetia illucens*) and yellow mealworm larvae (*Tenebrio molitor*), are rapidly gaining acceptance as one of the most promising sustainable alternatives for aquaculture feeds (Fukuda et al., 2022). Insects offer a compelling solution for sustainable feed production thanks to their high-efficiency conversion of organic waste into biomass, low environmental footprint, balanced amino acid profile, and richness of functional components. Requiring significantly less water and land than traditional animal husbandry, insect farming is also a production model compatible with circular economy principles. By cultivating insects on food industry waste and agricultural byproducts, they contribute to both waste reduction and resource recovery (nextProtein, 2019).

Yellow mealworm larvae are notable for their high protein (40–60%), fat (20–30%), and functional ingredient contents, and they offer successful nutritional results as a partial or complete replacement for fish meal (Makkar et al., 2014). Furthermore, the use of agricultural by-products in the production process offers environmental advantages by contributing positively to carbon and nitrogen cycles. The European Food Safety Authority (EFSA) has approved the use of certain species in fish feed in recent years following risk assessments related to insect proteins (EFSA, 2021), accelerating research, investment, and industrial applications in this area. Today, insect meals have been reported to provide high digestibility, improved growth performance, and improved intestinal health by replacing 25–75% of fish meal (CABI, 2023).

Consequently, the future of aquaculture depends not only on increasing production volumes but also on striking a balance between ecological sustainability, resource efficiency, and nutritional innovation. Integrating microalgae and microbial proteins, particularly insect proteins, into feed formulations, combined with environmentally friendly approaches that increase feed utilization and reduce eutrophication risks through enzymes such as phytase, will strengthen both the economic and ecological resilience of the sector. In this context, the yellow mealworm stands out as a strategic protein source for aquaculture feeds in terms of nutritional value, production flexibility, and environmental sustainability.

2. Yellow Mealworm (*Tenebrio molitor*)

2.1 Biology, Life Cycle, and Rearing Conditions

Among insect species considered as alternative protein sources in aquaculture production, the *Tenebrio molitor* (yellow mealworm) is the most widely used species. This species, belonging to the Tenebrionidae family of the Coleoptera order, is commercially cultivated, particularly in Europe and the Far East, due to its high nutritional content and ease of production. It is also an important ingredient in pet food, in addition to aquaculture (Büche, 2007; Fantatto et al., 2024).

Tenebrio molitor is an insect that undergoes complete metamorphosis (holometabolism) and prefers dark and moist microhabitats. Its life cycle consists of four primary stages: egg, larva, pupa, and adult. The developmental period of the species varies between 280 and 630 days, depending on environmental conditions (Gullan and Cranston, 2000). The eggs hatch within 4–12 days, developing into larvae, which feed and grow for a period of approximately 3–4 months. At this stage, the white larvae mature and then transition to the pupal stage; upon completion of metamorphosis, adults emerge. The optimum temperature range for rearing is 25–28°C. Relative humidity is generally maintained between 50% and 70%. Under appropriate temperature and humidity conditions, adults are capable of reproducing six times a year and are typically 12–20 mm in size (Makkar et al., 2014; Gullan and Cranston, 2000).

Separating the larval, pupal, and adult stages in rearing is critical to preventing cannibalistic behavior. For this purpose, 5–6 cm high, wide-bottomed containers are generally used. Separate containers should be provided for each stage, ensuring that individuals that remain immobile during the pupal stage are not consumed by the larvae or adults. Adults can be kept on egg cartons used as egg-laying areas; These materials also serve as mating and hiding surfaces (Kibar, 2018).

The mixture, referred to as "bedding" in nutrition, generally consists of flour or bran from grains such as wheat, barley, oats, and corn. This mixture serves both as a food medium and as a living substrate. The larvae's water needs are met by pieces of vegetables and fruits such as potatoes, carrots, apples, and lettuce. However, it is important to keep the environment well-ventilated, as excessive moisture can lead to mold and bacterial growth. Containers should be covered with mosquito nets to ensure air circulation and prevent the entry of other insects and mites. Vegetables and fruits should be placed so that they do not come into direct contact with the bedding, or a permeable material should be placed in between (Kibar, 2018). A thorough understanding of the biology and production conditions of T. molitor allows for the production of a highly productive and environmentally sustainable protein source. These characteristics make the species a strategic component in both aquaculture and the general feed industry.

2.2. Nutritional Composition

The yellow mealworm is gaining increasing importance as a sustainable alternative protein source in aquaculture. This widespread use is primarily due to the high protein content of the larvae and their balanced nutritional composition. Furthermore, the widespread distribution of species in the Tenebrionidae family provides advantages in terms of production and supply (Makkar et al., 2014).

The nutritional profile of the yellow mealworm during the larval stage is quite rich, averaging 53.2% protein and 34.5% fat on a dry matter basis (Ghosh et al., 2017). This high energy and protein density makes it an attractive feed ingredient from both nutritional and economic perspectives. Furthermore, analyses have shown that mealworm meal is rich in micronutrients such as zinc, selenium, biotin, pantothenic acid, and folic acid (Rumpold and Schlüter, 2013). In terms of amino acid composition, the proportions of essential amino acids such as isoleucine, leucine, and lysine, as well as unsaturated fatty acids, are similar to fish meal and soybean meal (Rumpold and Schlüter, 2013). Therefore, dried *T. molitor* meal has the potential to partially or completely replace fish meal (Wang et al., 1996; DeFoliart, 1992).

3. Usability of *Tenebrio molitor* in Fish Feeds

Recent studies have demonstrated that Tenebrio molitor meal can be successfully used as an alternative protein source in aquaculture feeds. Experimental feeding studies on various fish and crustacean species indicate that mealworm meal can replace fish meal at certain rates and generally has no adverse effects on growth performance, feed conversion ratio (FCR), or protein efficiency ratio (PER). In this context, the applicability of T. molitor protein to both freshwater and marine species is attracting increasing interest. The table below summarizes the various aquatic organisms for which mealworm meal has been evaluated as an alternative protein source, along with the main studies conducted on this subject.

Table 1. Use of mealworm (*Tenebrio molitor*) as an alternative protein source in different aquaculture species

Aquatic environment	Fish species (Scientific name)	% Insect meal inclusion	Results	References
Freshwater species	African catfish *(Clarias gariepinus)*	20%, 40%, 60%, 80%, 100%	no negative effects on growth, significantly higher lipid ratio,	Ng et al. (2001)
	Rainbow trout *(Oncorhynchus mykiss)*	25%, 50%	Reduction in ADC for crude protein, No effect in ADC for dry matter, organic matter and ether extract fillet protein increase, fillet lipid reduction, increase on groth parameters, eduction in the ratio of Σn3/Σn6 fatty acids of the dorsal muscle, overall significant reduction in the fillet in the EAA	Belforti et al. (2015), Iaconisi et al., (2018)
		5%, 10%, 20%	Increased ADC for crude protein, No effect on growth parameters	Chemello et al. (2020)
	Nile tilapia *(Oreochromis niloticus)*	25%, 75%	decreased growth by approximately 29%, affected the fatty acid profile of muscle.	Sanchéz-Muros et al. (2016)
	Yellow catfish *(Pelteobagrus fulvidraco)*	25%, 50%, 75%	No effect on growth parameters,	Su et al. (2017)
	Carp *(Cyprinus carpio)*	15%, 30%, 45%, 60%, 75%, 100%	Growth performance, flesh quality and skin color improved	Li et al. (2022)
	Mandarin fish *(Siniperca scherzeri)*	10%, 20%, 30%	Weight gain and efficiency of feed utilization; health-promoting effects	Sankian et al. (2018)
Marine Species	European sea bass *(Dicentrarchus labrax)*	25%	Increased ADC for protein	Gasco et al. (2016)
		50%, 100%	No effect on growth	Basto et al.

			performance, high rates of consumer-liking, a juicy texture.	(2023)
	Sea bream *(Sparus aurata)*	25%, 50%	Increased ADC for protein, water holding capacity and texture characteristics similar	Piccolo et al., 2017
	Blackspot seabream *(Pagellus bogaraveo)*	21%, 40%	Water holding capacity and texture characteristics similar, redness index in the skin increase	Iaconisi et al., 2017
	Turbot *(Scophthalmus maximus)*	15%, 30%, 45%, 60%, 75%	Defatted *Tenebrio molitor* meal at 15% level optimized the freshness.	Qi et al. (2024)
	Atlantic salmon *(Salmo salar)*	50%, 100%	No effect on growth performance, increase in IgD and IgT parameters	Habte-Tsion et al. (2024)
Crustaceans	Pacific White shrimp *(Litopenaeus vannamei)*	25%, 50%, 75%, 100%	No effect on growth performance, increase in lipid content, Methionine was the first limiting AA.	Panini et al. (2017)

Studies have shown that TM meal can successfully replace 50–100% of FM in omnivorous species (Tilapia, Common Carp, African Catfish). Growth performance (SGR) and feed efficiency (FCR) are generally unaffected at these levels (Wang et al., 2019). In carnivorous species (Rainbow trout, European sea bass, Atlantic salmon), it is recommended to limit TM substitution to 30–40%; in cases of excessive substitution, slight decreases in growth, reduced digestibility, or deterioration in the fatty acid profile may be observed (Gasco et al., 2018). This is attributed to the chitin content and ω-3 fatty acid deficiency in TM.

Chitin derivatives and bioactive peptides in TM meal enhance the innate immune responses of fish. Diets containing TM in European sea bass increased immune parameters such as lysozyme and trypsin inhibition (Gasco et al., 2018). Furthermore, at appropriate replacement levels, TM exhibits anti-inflammatory effects and supports the general health of the fish.

When the feeding substrate of TM larvae is enriched with microalgae or other plant-based ω-3 fatty acids, the fatty acid profile of the larvae can be improved in terms of long-chain ω-3 fatty acids such as EPA and DHA (Spranghers et al., 2017). This bioconversion approach addresses the most significant deficiencies in the nutritional quality of TM and is particularly important for diet optimization in carnivorous species.

In summary, the use of TM flour in aquaculture feeds is promising both in terms of improved growth performance and feed efficiency, as well as immune and health-supporting effects. Furthermore, nutritional quality deficiencies can be addressed by optimizing larval nutrition, making TM a functional and sustainable protein source in both freshwater and marine species.

4. Effects on Health and Immunity

Incorporating Tenebrio molitor (TM) into aquaculture feed formulations not only improves fish growth performance but also provides specific health benefits that strengthen their resistance to pathogens. These functional effects are associated with components derived from the TM's natural defense mechanisms (Gasco et al., 2018).

Antimicrobial Peptides (AMPs): Insects naturally produce antimicrobial peptides (AMPs) as part of their immune systems to defend against microorganisms. Tenebrio molitor larvae and their protein hydrolyzates contain bioactive peptides that can exhibit antimicrobial and antioxidant properties against pathogens such as bacteria and fungi. Incorporating these components into fish feed has the potential to offer an alternative strategy to the use of antibiotics against fish diseases (Cho et al., 2020).

Potential Immune System Benefits: Dietary supplementation with TM flour has been shown to enhance nonspecific (innate) immune responses in fish. Studies in European sea bass and rainbow trout found that diets containing TM significantly increased the activity of critical immune enzymes, such as lysozyme activity (antibacterial) and serum trypsin inhibition (associated with antiparasitic activity) (Gasco et al., 2018; Ge et al., 2023). TM has shown signals that may help reduce inflammation in fish by influencing the levels of serum biomarkers that support anti-inflammatory responses, such as ceruloplasmin and myeloperoxidase (Ge et al., 2023). A study in Atlantic salmon showed significant upregulation of immunoglobulin genes (IgM, IgD, and IgT) in fish fed a TM diet, suggesting stimulation of the adaptive immune system (Habte-Tsion et al., 2024). These immune-enhancing effects are thought to be due to the chitin/chitosan content in TM or the structural features of insect exoskeletons resembling those of parasites, activating the immune system as an immunostimulator (Ge et al., 2023).

Relationships with Gut Microbiota: Fish health and immunity are closely linked to the gut microbiota; changes in diet can directly affect this balance. The addition of TM meal to fish feed significantly affected the overall composition of the digesta microbiome in Atlantic salmon but did not significantly alter species richness (Habde-Tsion., 2024). In rainbow trout, complete substitution of fish meal with TM resulted in a slight modulation of the gut microbiota. In particular, a reduction in the number of some harmful or inflammation-associated bacterial taxa (Proteobacteria and the Neisseriaceae family) was observed (Terrova et al., 2021). Non-digestible components in TM, such as chitin/chitosan, act as prebiotics in the fish gut, supporting the growth of beneficial bacteria. This may positively impact nutrient metabolism, immune regulation, and disease resistance (Habde-Tsion., 2024).

5. Economic and Environmental Assessment

The yellow mealworm stands out as a sustainable alternative to traditional protein sources, and its economic feasibility and environmental advantages are decisive for the future of the aquaculture sector. Both the production costs and environmental impacts of TM make it a strategic option compared to traditional sources such as fish meal and soy.

Production Costs: While the production costs of insect meals are not yet fully competitive with traditional fish meal (FM), they have the potential to decrease rapidly with economies of scale and technological advances. The largest initial costs are the capital investment and energy requirements of highly automated vertical farms (Dewangan et al., 2025). However, the ability to grow TM on low-cost and abundant agricultural byproducts or food waste significantly reduces raw material costs (Arru et al., 2019). As industrial-scale production efficiency increases and regulatory approvals become clearer, the unit cost of TM flour is projected to be more resilient to price fluctuations in FM and soybean meal (SBM) (Arru et al., 2019; Dewangan et al., 2025).

Carbon Footprint and Environmental Sustainability: The most striking advantage of TM farming is its minimal environmental impact compared to conventional livestock farming:

- **Low greenhouse gas emissions:** TM production produces significantly fewer greenhouse gases (methane and nitrous oxide) per kilogram of protein than traditional livestock farming (Oonincx and De Boer, 2012).
- **Minimal resource consumption:** TM production, unlike traditional protein sources, requires low land use and minimal water requirements. This provides a significant advantage in aquaculture feed production, particularly in regions with limited water resources.

- **Reducing pressure on fish stocks:** Substituting TM flour with FM reduces overfishing and pressure on marine ecosystems, thereby contributing to the conservation of marine biodiversity (Makkar et al., 2014).

Contributions to Local Production and the Circular Economy

TM is a protein source that fits into local food systems and the circular economy:

- **Waste utilization (circularity):** It transforms non-food-grade waste, such as TM larvae, vegetable scraps, and milling by-products, into high-quality protein. This process reduces waste volume, adds valuable nutrients to the food cycle, and lowers waste management costs (Arru et al., 2019).
- **Local protein source:** Insect farms can be established in almost any geography without relying on plant raw materials (e.g., soy imports) or marine resources. This local production capability reduces supply chain risks and strengthens the protein self-sufficiency of regional aquaculture sectors (Dewangan et al., 2025).
- **Fertilizer use:** Excrement and other waste (frass) generated during TM production can be recycled into agriculture as a nutrient-rich organic fertilizer. Thus, production optimizes waste management and contributes to agricultural production, in line with circular economy principles (Arru et al., 2019).

The economic and environmental advantages of TM cultivation are not limited to cost reduction or environmental sustainability; they also offer significant opportunities for fish health, local production capacity, and integration with the circular economy. For these reasons, TM is considered a key ingredient in next-generation sustainable aquaculture feeds.

6. Future Perspectives

Reaching the full potential of yellow mealworm protein (*Tenebrio molitor*, TM) in aquaculture depends not only on scientific and technical advancements but also on overcoming economic, legal, and industrial barriers.

Commercialization and Regulatory Barriers

- Cost Competitiveness: For insect meal to be competitive against fish meal in the long term, production costs must be reduced and economies of scale achieved. The efficiency of automation and vertical farm processes, which require high capital investments, play a critical role in this (Dewangan et al., 2025).

- Regulatory Frameworks: While the European Union (EU) and other competent authorities have approved the use of insect protein in aquaculture feeds, strict regulations and food safety standards on the substrates on which the insects feed (e.g., food waste or by-products) remain a significant obstacle to commercialization. The safety and traceability of the substrates are essential for regulatory approval of the final product (Arru et al., 2019).

Consumer Acceptance: The indirect use of TM in fish feed formulations does not pose a major problem in terms of overall consumer acceptance. However, transparency and effective communication are critical, particularly regarding its effects on the fatty acid profile and nutritional quality of fish meat.

Areas for Improvement

1. **Fatty Acid Profile Enrichment:** The most significant nutritional limitation of TM is its deficiency in long-chain ω-3 fatty acids (EPA/DHA). To address this deficiency, bioconversion processes should be optimized by adding Schizochytrium *sp.* or other microalgae to the larval diet (Spranghers et al., 2017).
2. **Chitin Management:** High TM substitution rates can cause digestive difficulties. Dehulling, enzymatic hydrolysis, and other further processing techniques need to be developed to reduce chitin content or increase its functional benefits (Gasco et al., 2018).
3. **Species-Specific Optimization:** Fish species have different nutritional and immune requirements. Optimal substitution levels of TM for different species (especially carnivores) should be determined through long-term experiments based on growth and health parameters.

The Long-Term Role of Insect Protein in Fish Feeds

In the future, TM protein is not expected to be the sole replacement for FM or SBM in fish feeds. Instead, TM will play a permanent role as the third essential protein source in aquaculture diets thanks to its high protein content and bioactive functional benefits. This approach will reduce dependence on FM, balance feed costs, and contribute to the creation of a more flexible, circular, and sustainable feed portfolio.

The potential for TM production and utilization is increasing globally, and in parallel with regulatory and industrial investments in sustainable protein sources, particularly in Europe, North America, and Asia, TM is expected to become a strategic component in aquaculture (Gasco et al., 2018; Arru et al., 2019; Dewangan et al., 2025).

7. Conclusion and Recommendations

Yellow mealworm (*Tenebrio molitor*) protein has strong potential as an alternative protein source in sustainable aquaculture feeds. The high protein content and balanced amino acid profile of the larvae support fish growth performance, while unsaturated fatty acids and other functional components positively impact meat quality and overall fish health. Furthermore, chitin and antimicrobial peptides have supportive effects on the immune system and gut microbiota.

Worldwide studies indicate that yellow mealworm meal can be successfully used as a 10–30% replacement for fish meal in feed formulations. Substitutions at these rates generally do not result in adverse effects on feed conversion ratio (FCR), protein efficiency ratio (PER), or growth performance. However, more comprehensive and species-specific studies are needed to determine the optimal substitution rate and to evaluate long-term effects in different fish species.

Yellow mealworm production contributes to environmental sustainability with its low land and water requirements. It also supports the circular economy approach through the valorization of agricultural by-products. An economically viable production model can be established in Turkey and other countries with appropriate legislative regulations, R&D incentives, and local production investments.

Accordingly, the commercialization of yellow mealworm protein and increased industrial-scale production will enable its more widespread use in fish feed. Clarifying legislation and quality standards, along with formulation optimization and the development of production technologies, will significantly increase the potential utilization of this protein.

In conclusion, Tenebrio molitor protein offers a sustainable alternative to traditional protein sources with its nutritional value, functional properties, and environmental advantages. With appropriate formulation strategies and economical production conditions, it will become a key ingredient in fish feed, reducing environmental impact and contributing to sustainable aquaculture goals.

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Chapter 7

Provisioning Services of Mussel Aquaculture: A Brief Review of Food and Bio-Based Products

Meryem Yeşim ÇELİK[1]

1. Introduction

Mussel cultivation is an essential practice for sustainable seafood production, contributing significantly to both local economies and marine ecosystems. Bivalve molluscs play a critical role in global seafood production. The dataset from 1950 to 2022 demonstrates a consistent increase in species, emphasizing that bivalve molluscs, such as mussels, have continually added to the global seafood supply (FAO, 2024). In 2022, global mussel production was approximately 1.93 million tonnes, of which about 431 thousand tonnes (22.38%) were produced in Europe (FAO, 2024). Following Spain, China, and Chile, it is the third-largest mussel producer worldwide, accounting for 44.6% of European production and 9.98% of global production (Labarta & Fernández-Reiriz, 2019). The European Market Observatory for Fisheries and Aquaculture Products (EUMOFA, 2022) reported that mussels were among the most farmed species in Europe. The main types were sea mussels (195,000 tonnes), blue mussels (135,000 tonnes), and Mediterranean mussels (79,000 tonnes). These figures constitute a significant part of the total EU aquaculture production (STECF, 2025). This distribution, along with the long-line and raft systems in Spain, France, Italy, Ireland, and the Netherlands. Mussels are vital for strengthening marine ecosystems and supporting local economies across the EU, especially in areas with established aquaculture. The EUMOFA "Price Structure Analysis" report evaluates demand channels, market segmentation, and value-added chain margins for mussels, emphasizing their importance in the European seafood market in terms of production, price structure, and value.

Ecologically, mussels are classified as 'ecosystem engineers' due to their capacity to enhance aquatic ecosystem functions. They contribute to increased water transparency by actively filtering seawater, thereby influencing water clarity and nutrient dynamics. They influence the benthic-pelagic cycle of

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nutrient elements through biodeposition. Mussel facies create habitats for macrobenthic species (Fig. 1).

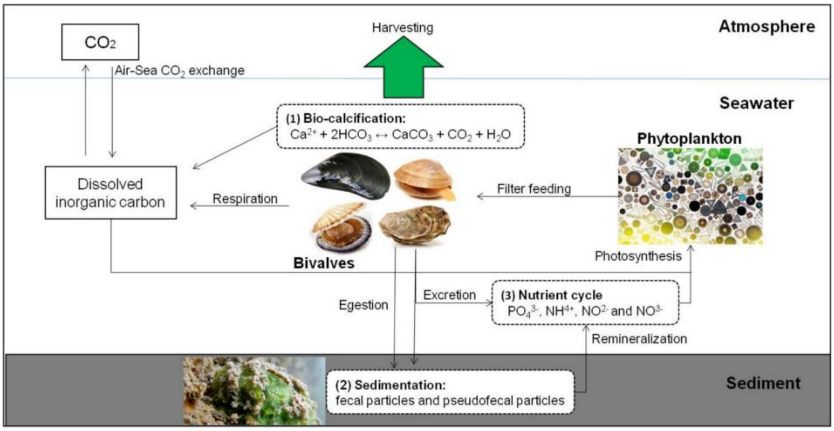

Figure 1. Contribution of bivalve farming to the marine carbon sink through three interrelated processes: (1) bio-calcification, which stores carbon in shell calcium carbonate ($CaCO_3$); (2) enhanced sedimentation of organic matter via biodeposition, increasing long-term carbon burial in sediments; and (3) stimulation of phytoplankton growth by nutrient recycling and improved water clarity (Filgueria et al., 2018; Zhang et al., 2025)

The cultivation of bivalve molluscs benefits communities by providing versatile ecosystem services beyond just food production. In a comprehensive study by Van der Schatte Olivier et al. (2020), both the market valuation and the ecological significance of non-market ecosystem services associated with bivalve aquaculture were systematically quantified. The research estimates the total market value of provisioning services, including products such as meat, pearls, shells, and bird feed, at approximately USD 23.9 billion. Furthermore, cultured bivalves provide critical regulatory services by removing approximately 49,000 tonnes of nitrogen and 6,000 tonnes of phosphorus annually, with an estimated economic valuation of around USD 1.2 billion. The overall global economic valuation of ecosystem services attributable to non-food bivalve cultivation is approximately USD 6.47 billion, with a confidence interval ranging from USD 2.95 billion to USD 9.99 billion.

The Millennium Ecosystem Assessment (MEA, 2005) created a detailed framework for understanding how ecosystem processes support human well-being by classifying ecosystem services into four main categories: provisioning, regulating, supporting, and cultural. Within this framework, the roles of Mytilus galloprovincialis in marine ecosystems can be understood as specific contributions to these service categories. *M. galloprovincialis* provides multiple ecosystem services, including the regulating services of water purification through biofiltration and coastal protection via reef and bed formation; supporting services such as habitat provision for numerous marine species, life cycle maintenance, nutrient recycling, and biodiversity enhancement; and provisioning and cultural services through its use as a sustainable food source, as well as in recreational fishing, tourism, and cultural enrichment (Table 1). Thus, M. galloprovincialis aquaculture not only supports food security but also improves ecosystem health and cultural importance, illustrating the MEA's core idea that human well-being is deeply connected to the health and functioning of marine ecosystems.

Table 1. Ecosystem services provided by mussels (Puri et al., 2021)

Ecosystem service class	Mussel-provided ecosystem service	Benefits for humans
Regulating	Biofiltration	Improved water quality
	Coastal protection (through reef and bed formation)	Shoreline stabilization, erosion prevention
	Nutrient cycling and storage	Water purification and nutrient balance
	Habitat and substrate for many species	Biodiversity maintenance
Supporting	Life cycle maintenance (spawning and nursery grounds)	Fishery resource sustainability
	Environmental monitoring (bioindicator role)	Assessment of ecosystem health
Provisioning	Food for humans	Nutritious and sustainable protein source
	Food for other species	Supports higher trophic levels
	Products from shells and byssus	Raw materials for medicine, industry, and biomaterials
Cultural	Recreational and educational value (fishing, ecotourism)	Recreation, tourism, education
	Cultural and spiritual value	Connection with marine heritage and conservation awareness

2. Provisioning Services

Provisioning services are defined as tangible economic or material outputs produced by ecosystems that directly enhance human well-being (MEA, 2005). Mussel aquaculture effectively demonstrates this service category by providing nutrition, raw materials, and bio-based products, thereby supporting local economic growth and human health.

2.1. Food and Nutritional Value

The nutritional benefits of mussels extend beyond their protein content (Fig 2). Mussel proteins are of high biological quality and contain essential amino acids in optimal ratios for human nutrition.

Figure 2. Nutritional content of mussels (Yaghubi et al., 2021)

On average, the composition of fresh mussel meat contains approximately 12–14% protein, 3–6% carbohydrates, 1.6–2.2% fat, 2–3% ash, and 76–82% moisture (Table 2). In dried products, these proportions increase to 36–67% in protein and 6–12% in fat. These values reflect the seasonal, locational, and nutrient availability-sensitive nature of mussel cultivation (Miller et al., 2023).

Mussels have a relatively low total lipid content (usually 1.6–2.2% in fresh meat), but up to 50–60% of these lipids are long-chain omega-3 polyunsaturated fatty acids (PUFAs), especially EPA and DHA (Miller et al., 2023). Carbohydrate levels are moderate (3–6%), and water content is high (76–82%), making mussels a low-calorie yet nutrient-rich food source. They also supply essential micronutrients that are often scarce in land-based foods, such as vitamin B12, iron, and omega-3 fatty acids, crucial for preventing nutritional deficiencies (Wright et al., 2018). For example, analyses of Black Sea mussels reveal that total free amino acids make up about 0.7% of the meat, with roughly 40% of this being essential amino acids (Mititelu et al., 2022).

Table 2. Basic chemical composition (g/100 g) of fresh and dried meat of Mytilidae species (Miller et al., 2023)

Content	Fresh mussel meat (%)	Dry mussel meat (%)	
Protein	12–14	36–67	Having a high biological value, seasonally variable
Carbohydrate	3–6	10–25	The energy source depends on plankton feeding.
Lipid	1.6–2.2	6–12	Low total fat, but high n-3 PUFA ratio
Ash	2–3	2–25	Mineral sources (Ca, Mg, Zn, Fe, I)
Moisture	76–82	-	High water content in fresh meat

This numerical composition conforms to the scientific principle that mussels are a 'high nutrition / low input cost' food: since no external feed is used, input costs are reduced while providing consumers with highly bioavailable proteins and valuable fatty acids. In this context, mussels could serve as a strategic option for enhancing food security, dietary diversity, and protein supply in coastal communities.

Mussel meat is increasingly recognized as a sustainable and high-quality animal protein source (Blunt et al., 2015). While the global population is expected to reach 9.7 billion by 2050, the demand for environmentally friendly and economically viable high-protein foods is growing (Sadowski et al., 2024). Traditional protein sources such as red meat, dairy products, and other seafoods produce high greenhouse gas emissions, whereas mussels, which can be farmed without antibiotics or supplemental feed, offer a low environmental impact with a carbon footprint of only 0.6 kg CO_2 per kg (Ghaly et al., 2013; Małecki et al., 2021). In 2020, global mussel production was about 2 million tonnes, and they are rich in high-quality protein, biologically active lipids, vitamins, and essential minerals. A 100-gram portion of raw mussel meat provides about 12.6–13.0 grams of protein and has an amino acid score of 107, making it well-suited to human nutritional needs (Venugopal and Gopakumar, 2017). These qualities position mussel meat as an important potential protein source for future food security and sustainable systems (Koodathil et al., 2025).

2.2. Bio-Based Products and Industrial Uses

Mussels are valuable not only as seafood but also as sustainable sources of high-value biomaterials. Two major by-products, byssus threads and shells, have attracted considerable scientific and industrial interest due to their structural, chemical, and mechanical properties.

2.2.1. Byssus-Derived Materials

The byssus, a bundle of fine protein threads secreted by mussels to anchor themselves to surfaces, demonstrates outstanding adhesion in wet and salty environments (Deming, 1999). This ability comes from the high concentration of catechol- and DOPA-containing proteins, which form strong covalent and metal bonds even underwater (Harrington et al., 2016) (Figure 2).

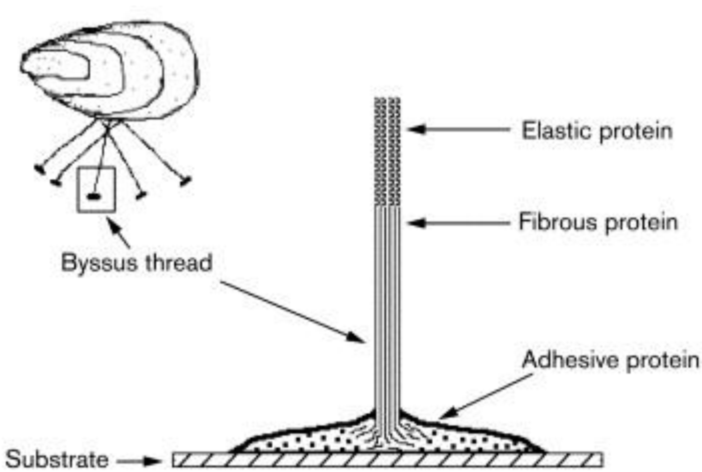

Figure 2. The structure and composition of byssus attachment threads for *Mytilus edulis* (Deming, 1999).

Recent studies have shown that byssus-derived biomolecules inspire the design of multifunctional materials. Due to the high adhesive strength of mussel byssus and their protein-based biopolymer structures, it is reported that they are now used in a wide range of advanced technological applications. Materials derived from byssus components are effectively used in biomedical adhesives, biocompatible hydrogels and tissue engineering materials, nanoparticle-based drug delivery systems, cell culture and biomedical surface coatings, composite nanofibers, and biostructure scaffolds, as well as in the development of metal-bound composite films and self-healing materials. Moreover, it has been shown that waste byssus fibers from cultivation can be partially hydrolyzed to produce pH-sensitive biofilm materials suitable for water purification and paint removal (Harrington et al., 2016; Yang et al., 2018).

2.2.2 Shell-Derived Calcium Carbonate Materials

Mussel shells attract attention not only as biological residues of marine organisms but also as a versatile source of biomaterials due to their high content of calcium carbonate ($CaCO_3$). This biogenic calcium carbonate is an environmentally friendly, abundant, and low-cost raw material due to its natural nature. Therefore, the utilization of shell waste offers significant opportunities both economically and ecologically (Hart, 2020).

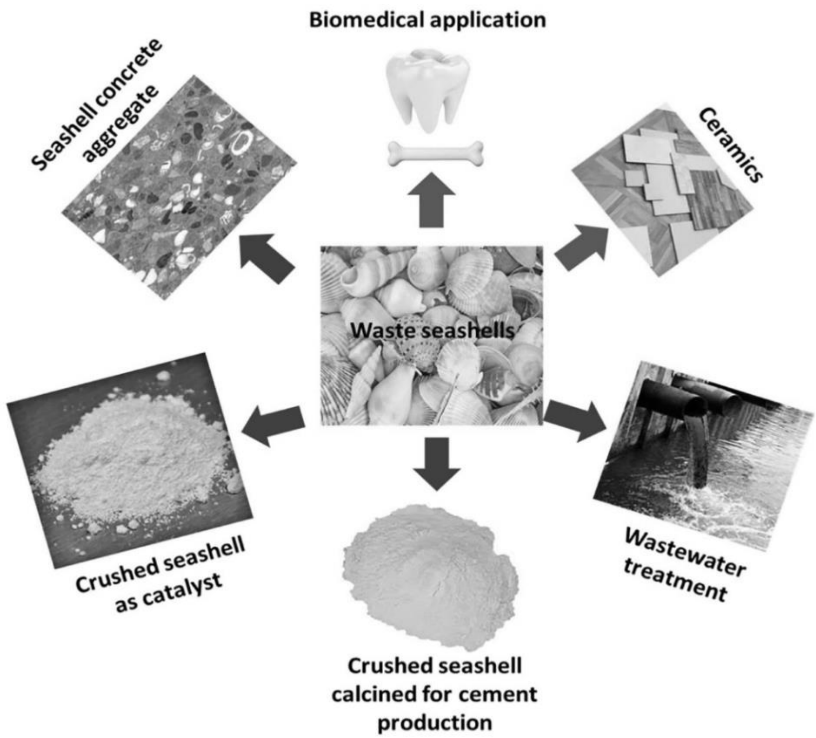

Fig. 3. Waste seashells can be used in various sustainable applications, including biomedical materials, ceramics, wastewater treatment, catalysts, cement production, and concrete aggregates (Hart, 2020)

As highlighted in the study by Popovic et al. (2023), mussel shells have traditionally been employed as soil amendments, especially in the Galicia region of Spain. The primary rationale for this practice is that calcium carbonate, the predominant constituent of shells, enhances agricultural productivity by elevating the pH of acidic soils. Additionally, recent studies have shown that mussel shells can be used as environmental treatment materials in soils with heavy metals because of their binding and adsorbent properties. They stated that due to its high pH value and porous microstructure, it can serve as an effective sorbent for removing toxic metals such as lead, cadmium, and copper from soil. Therefore, shell waste helps reduce environmental pollution and promotes sustainable waste management practices (Santás-Miguel et al., 2022). Similarly, it has been shown that mussel shell waste can be used innovatively in the construction industry. El Biriane and Barbachi (2021) demonstrated that recycled mussel shells can be partially substituted for natural aggregates in concrete and mortar mixtures, enabling the production of "ecological concrete". Such materials are especially suitable for use in non-load-bearing building components, which helps lower costs and decrease reliance on natural resources. Using husk powders or crushed husk particles as aggregates provides mechanical strength comparable to traditional materials while reducing greenhouse gas emissions during production. In the study conducted by Petti et al. (2024), the seashells found in fine-grained muddy sediments obtained through seabed dredging were decomposed, cleaned, dried, ground, and then used as a cement-like binding agent. It has been stated that ground shell powders increase the durability of sediments by replacing some of the cement, thus providing both more stable and environmentally friendly building materials. It was emphasized that this approach is a striking example of "green engineering" in terms of using one waste (mussel shell) in the remediation of another waste (dredged sediment). Additionally, this method lowers the carbon footprint by reducing cement consumption and offers an alternative binding solution for sustainable infrastructure projects. Thongnopkun et al. (2025) suggests that green mussel shell waste can be ground into different sizes and utilized in the production of artificial sand. According to research, the variable grain size distribution of shell powders makes them usable in various industrial applications, especially in the production of artificial sand. This process does not use harmful chemicals, prioritizes energy efficiency, and develops a production method that is both environmentally friendly and economical. Thus, mussel shell waste from the fishing and food industries becomes a valuable industrial input. Therefore, the integration of mussel shells into building materials is considered an environmentally responsible solution that aligns with the circular economy approach.

2.3. Functional Hydrolysates and Feed Applications

Mussel meat has also proven to be a promising biomass source for biotechnological applications.

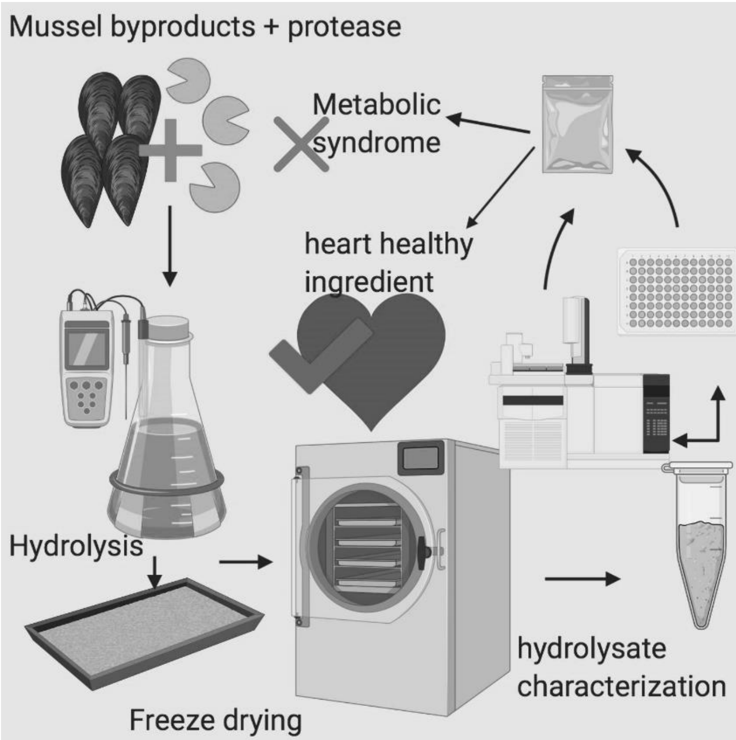

Fig. 4. Schematic diagram of mussel by-product hydrolysis and processing into bioactive compounds (Naik et al., 2020)

Recent research has shown that special mixtures derived from mussel meat are notable not only for their nutritional value but also for their beneficial effects on health (Cunha et al., 2021; Derkach et al., 2024; Lu et al., 2025; Islam et al., 2022). These mixtures are obtained by naturally enzymatically breaking down the proteins in mussel meat, and the resulting small protein fragments, known as peptides, can inhibit enzymes associated with certain diseases in the body (Naik et al., 2020; Lu et al., 2025). According to studies, these peptides exhibit properties such as neutralising harmful substances in the body (antioxidant effects) and helping to regulate blood pressure and blood sugar levels (Islam et al., 2022; Bougatef et al., 2024; Shekoohi et al., 2024). Components derived from mussels have been found in laboratory experiments to have protective potential, particularly against cardiovascular health issues, diabetes, and cell damage related to ageing (Cunha et al., 2021; Derkach et al., 2024; Lu et al., 2025). Furthermore, it is believed that these natural components could be utilised in foods, dietary supplements, cosmetic products, and health-supporting formulations (Shahidi and Saeid, 2025). However, scientists emphasise that further research is needed to determine whether these promising results are equally applicable to humans (Cunha et al., 2021; Bougatef et al., 2024).

The use of mussel meal as an alternative ingredient in animal nutrition has gained increasing importance in recent years, both in terms of nutritional value and sustainability potential. Studies on various marine and freshwater species have shown that mussel-based flours can provide valuable sources of protein and lipids without adversely affecting animal health. In rainbow trout (*Oncorhynchus mykiss*), freshwater mussel flour supported normal histological structure and achieved growth performance comparable to traditional fish-based diets (Sicuro et al., 2023). Research conducted on gilthead seabream (Sparus aurata) has reported that supplementing with mussel meal improves feed quality by increasing levels of polyunsaturated fatty acids such as DHA and EPA (Privileggio et al., 2024). In poultry production, golden mussel meal has been successfully used as a mineral source in place of limestone, maintaining growth and bone development in broiler chickens (Jablonski et al., 2025). Recent additional studies have shown that green mussel (Perna viridis) meal improves gut health and feed digestibility in Asian sea bass (Lates calcarifer), and when cadmium contamination levels are kept low, it results in higher growth performance (Rasidi et al., 2024). Similarly, calcined mussel shells derived from Corbicula sumatrana have been found to be effective as a mineral supplement and natural preservative at levels of 3% and 6% in quail diets (Khalil & Montesqrit, 2024). These findings emphasise the importance of mussel meal as an environmentally friendly and nutrient-rich feed component, while also highlighting the need to strengthen broodstock management strategies and increase hatchery-based production for sustainable scaling (Padín et al., 2024).

Conclusions

Mussel aquaculture is one of the most tangible and sustainable examples of provisioning ecosystem services in marine environments. Besides serving as a nutrient-rich food source, mussels offer a variety of valuable bioresources, including byssus threads and calcium carbonate-rich shells that can be turned into high-value biomaterials. Together, these outputs demonstrate that mussel farming supports food security, material innovation, and local economic growth. Building on these benefits, the production of low-impact protein and bio-based industrial materials continues to grow. Mussel aquaculture demonstrates the principles of the circular blue economy by utilizing all parts of the organism, from meat to shell, to produce valuable products. This comprehensive biomass utilization minimizes waste, increases value creation, and strengthens the connection between ecological sustainability and socioeconomic resilience. In this context, the provisioning services of mussel cultivation should be viewed not just as the extraction of biological products but as an integrated process that connects ecology, economy, and technology. By maintaining this balance, mussel farming can continue to serve as a model for ecosystem-based aquaculture and a catalyst for sustainable coastal livelihoods within the evolving blue bioeconomy framework strategies.

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