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Editör
Prof. Dr. Funda TURAN

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Chapter 1

Current Status and Molecular Perspectives on the Phylogeny and Phylogeography of Gurnards (*Triglidae, Dactylopteridae, Peristedidae*) in the Mediterranean Sea

Cemal TURAN[1]

Abstract

Gurnards are ecologically and commercially significant demersal fishes that are widely distributed across the Mediterranean Sea. Despite their ecological importance and commercial value, the systematics and population genetics of these species have long been challenging due to morphological plasticity and insufficient molecular data. This review synthesizes current knowledge on the molecular phylogeny, phylogeography, and conservation status of gurnard species belonging to the families *Triglidae, Dactylopteridae*, and *Peristedidae,* with a particular focus on Turkish marine waters, where the most comprehensive recent studies have been conducted. This review highlights substantial knowledge gaps, including the lack of pan-Mediterranean genomic studies, and outlines future research priorities to inform the sustainable management and conservation of these vulnerable fish populations.

Keywords: Gurnards; *Triglidae;* Mediterranean; molecular phylogeny; phylogeography; conservation genetics; mitochondrial DNA

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1. Introduction

Gurnards (*Triglidae, Dactylopteridae, and Peristedidae*) are a diverse group of bottom-dwelling scorpionfishes that play a pivotal role in benthic food webs across temperate and tropical seas. They are characterized by their large, armored heads, free pectoral-fin rays used for substrate exploration, and a generally opportunistic feeding strategy that targets epibenthic and nektobenthic invertebrates (Colloca et al., 2019; Stagioni et al., 2012). In the Mediterranean basin, gurnards are represented by multiple genera, including *Chelidonichthys*, *Eutrigla*, *Lepidotrigla*, *Trigla*, *Trigloporus*, *Dactylopterus*, and *Peristedion*, with Turkish marine waters hosting nine distinct species (Turan et al., 2007; Froese & Pauly, 2025).

The systematics and phylogeography of Mediterranean species have received gate attention (Turan, 2006, 2008; Ivanova & Dobrovolov, 2006; Riccioni et al., 2017; Turan et al., 2019, 2024, 2025). Despite their ecological importance and commercial value, the systematics and population biology of Mediterranean gurnards have received relatively little attention. Traditional species identification relies on morphological traits such as fin-ray counts, lateral-line scale structure, and cephalic spine patterns but these characters often exhibit significant phenotypic plasticity in response to environmental conditions (Swain & Foote, 1999). Consequently, taxonomic uncertainties persist, and species boundaries remain ambiguous. In recent decades, molecular genetic techniques have become essential for resolving these issues. Mitochondrial DNA (mtDNA), due to its maternal inheritance, absence of recombination, and rapid evolutionary rate, has proven particularly useful for investigating both deep phylogenetic relationships and shallow population structure in marine fishes (Avise, 1994; Meyer, 1994).

Over the past decade, a series of studies focusing on the Mediterranean and Turkish marine waters have significantly advanced our understanding of the molecular systematics and phylogeography of gurnards (Uyan & Turan, 2017; Turan et al., 2016; Boudaya et al. 2020; Ferreira et al. 2024; Turan et al., 2026). These investigations, primarily based on morphological characters, mtDNA 16S ribosomal RNA (16S rRNA) and Cytochrome c oxidase subunit III (COIII) genes, have provided novel insights into the evolutionary relationships, population connectivity, and conservation status of these species. This review aims to synthesize these findings and place them within the broader Mediterranean context. We specifically address: (1) the current phylogenetic framework for *Triglidae, Dactylopteridae, and Peristedidae*; (2) the phylogeographic patterns and genetic structure of key populations; (3) the discordance between molecular and morphological data; and (4) the conservation implications for threatened species and populations.

2. Molecular Systematics and Phylogenetic Relationships

2.1 Monophyly and Higher-Level Relationships

Comprehensive phylogenetic analyses using mtDNA COIII and 16S rRNA sequences consistently support the monophyly of the family Triglidae (Turan et al., 2026; Riccioni et al., 2017). In the most extensive study to date, examining nine species from Turkish seas, Bayesian inference (BI) and neighbour-joining (NJ) trees based on a combined 1161-bp dataset (COIII + 16S rRNA) recovered five distinct clades (Turan et al., 2026). **Figure 1** illustrates the consensus phylogenetic topology derived from these combined datasets, revealing the evolutionary relationships among all studied gurnard families. Five major clades are resolved: (I) *Lepidotrigla cavillone* + *L. dieuzeidei* (sister species with minimal divergence); (II) *Chelidonichthys cuculus* + *Eutrigla gurnardus* + *Trigla lyra* (notably, *C. cuculus* does not cluster with its congeners); (III) *Trigloporus lastoviza* + *Chelidonichthys lucerna*; (IV) *Dactylopterus volitans* (Dactylopteridae); and (V) *Peristedion cataphractum* (Peristediidae), which is the most divergent lineage. Bootstrap values ≥ 70% are shown at the nodes. *Dicentrarchus labrax* was used as the outgroup.

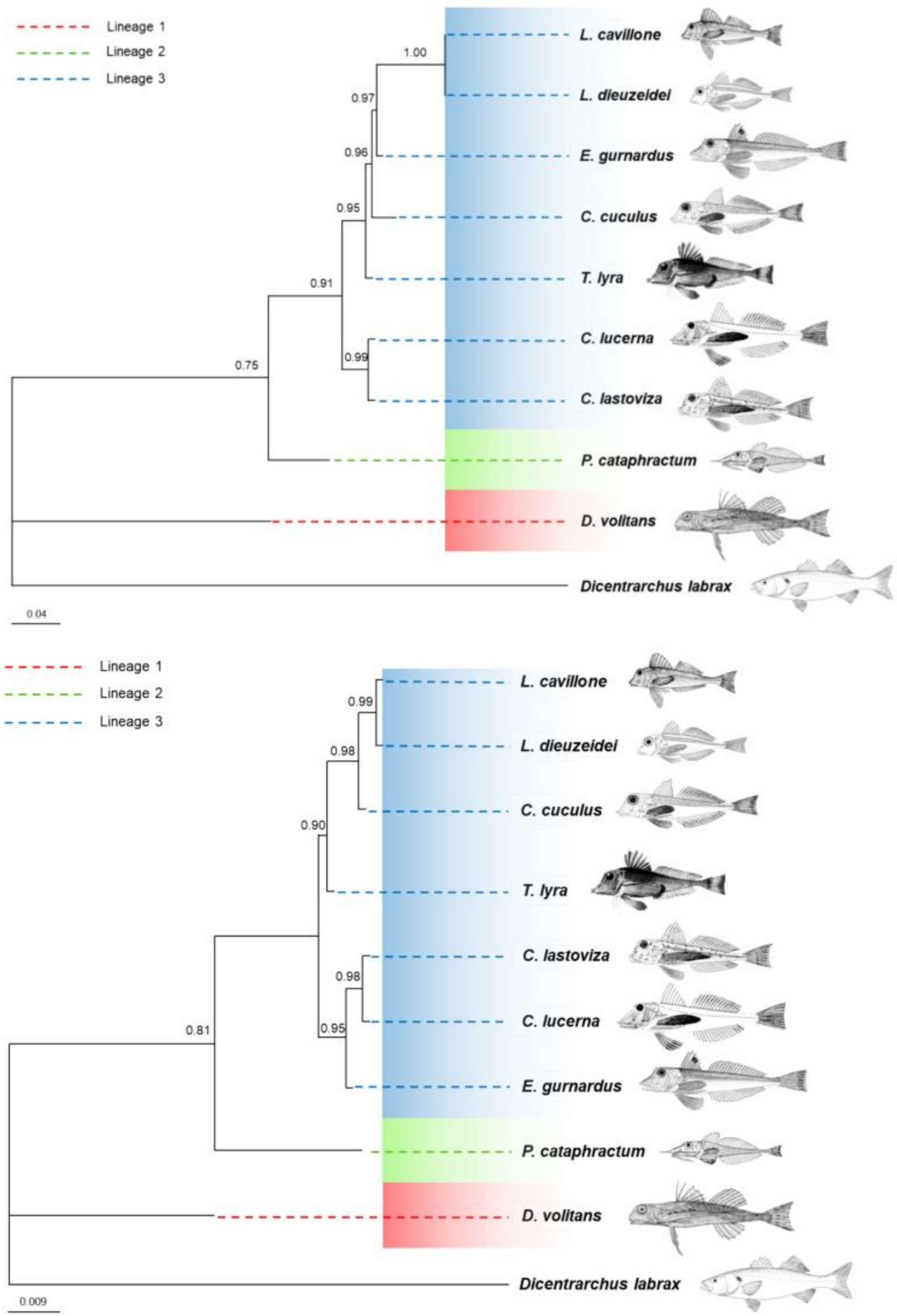

Figure 1. Molecular phylogenetic relationships of gurnard species from Turkish marine waters based on combined mtDNA COIII (above figure) and 16S rRNA gene (below figure) sequences. (Adapted from Turan et al., 2026).

The Triglidae species formed a single, well-supported clade, while *Dactylopterus volitans* (Dactylopteridae) and *Peristedion cataphractum* (Peristediidae) consistently branched separately, showing high genetic differentiation (COIII distances of up to 0.4856 for *C. cuculus* vs. *P. cataphractum*). These findings align with recent phylogenomic classifications that place Peristediidae as a subfamily (Peristediinae) within Triglidae (Betancur-R et al., 2017; Van der Laan et al., 2026).

2.2 Paraphyly of *Chelidonichthys* and Generic Instability

One of the most significant findings from recent molecular studies is the non-monophyly of the genus *Chelidonichthys*. While *C. lucerna* and *C. lastoviza* (formerly *Trigloporus lastoviza*) form a stable sister group across both COIII and 16S rRNA trees, *C. cuculus* consistently fails to cluster with its congeners. Instead, *C. cuculus* is placed in a clade with *Eutrigla gurnardus* and *Trigla lyra*, with high posterior probability support (COIII: PP = 0.96 with *E. gurnardus*; 16S rRNA: PP = 0.90 with *T. lyra*) (Turan et al., 2026). This phylogenetic instability suggests that the current generic classification of *Chelidonichthys* is paraphyletic and warrants taxonomic revision. The discordance may stem from incomplete lineage sorting, ancient hybridization, or convergent morphological evolution that has historically masked deeper genetic divergences. Similar patterns have been observed in other marine fish groups where morphology fails to reflect underlying phylogeny (e.g., Betancur-R et al., 2013). Future studies incorporating nuclear markers and expanded taxon sampling are essential to resolve the boundaries of *Chelidonichthys* and to determine whether *C. cuculus* should be reassigned to a distinct genus.

2.3 The *Lepidotrigla* Species Complex and Cryptic Diversity

The species pair *Lepidotrigla cavillone* and *L. dieuzeidei* exhibits the lowest genetic divergence among all studied gurnards, with pairwise distances of 0.0022 for COIII and 0.0023 for 16S rRNA (Turan et al., 2026). These values are close to intraspecific levels observed in other marine teleosts (e.g., Bineesh et al., 2015) and suggest either very recent speciation or ongoing gene flow. Morphologically, the two species are distinguished by subtle traits, including the presence of supraocular spines in *L. cavillone*, differences in cleithral spine length, and the extension of the free pectoral-fin rays (Turan et al., 2007). The extremely low molecular divergence, combined with limited geographical sampling (primarily Turkish waters), raises the possibility that these taxa represent a single species with ecophenotypic variation or a species complex awaiting broader phylogeographic assessment. A similar pattern of low mtDNA divergence but distinct morphology has been documented in other Mediterranean fish groups (e.g., *Spicara* species; Turan, 2011). Given that the Bayesian Poisson Tree Processes (bPTP) species delimitation analysis did not separate them as distinct lineages, further investigation using nuclear markers and comprehensive geographic sampling is critical to clarify their taxonomic status (Turan et al., 2026).

2.4 Phylogenetic Placement of *Trigla*, *Trigloporus*, and *Eutrigla*

Phylogenetic analyses based on 16S rRNA reveal a close genetic affinity between *Trigla lyra* and *Trigloporus lastoviza*, with an interspecific distance of only 0.00289 (Uyan & Turan, 2017; Turan et al., 2026). This value is well below typical genus-level divergences in marine fishes, suggesting that the currently recognized genera *Trigla* and *Trigloporus* may be synonymous. This conclusion is further supported by morphological overlap and historical taxonomic confusion regarding these groups (Ramon, 1997). Similarly, *Eutrigla gurnardus* shows moderate genetic differentiation from other Triglidae and is phylogenetically positioned near *C. cuculus* in some analyses, despite its distinctive morphology (e.g., a large black spot on the first dorsal fin). These findings collectively indicate that the current generic-level classification of Mediterranean gurnards requires comprehensive revision using an integrative taxonomic framework that combines molecular, morphological, and ecological data.

3. Phylogeography and Population Genetics

3.1 Genetic Diversity and Structure of *Chelidonichthys lucerna*

The tub gurnard, *Chelidonichthys lucerna*, is the most widespread and commercially exploited gurnard in Turkish waters, providing an excellent model for studying phylogeographic patterns. A population genetic study based on mtDNA 16S rRNA (809 bp) across five regions, the Black Sea (Düzce), Sea of Marmara, Aegean Sea (İzmir Bay), and two Mediterranean sites (Antalya Bay and İskenderun Bay) revealed significant genetic structuring (Uyan & Turan, 2017). The key diversity metrics for each population are summarized in **Table 1**, while the genetic relationships among populations are depicted in **Figure 2**. The tree reveals that the two Mediterranean populations (NMS1 and NMS2) cluster together, the Aegean population (AS) appears as a separate branch, while the Black Sea (BS) and Marmara (MS) populations show distinct positioning, consistent with the Dardanelles Strait acting as a partial phylogeographic barrier.

Overall, 14 distinct haplotypes were identified across all 125 specimens, with an average haplotype diversity (Hd) of 0.729 and a mean genetic diversity among populations of 0.0079 (Uyan & Turan, 2017). Marked regional differences were observed: İskenderun Bay exhibited the lowest genetic diversity (π = 0.000462) and the fewest haplotypes (Nh = 3), while the Sea of Marmara showed the highest nucleotide diversity (π = 0.001858) alongside five haplotypes. The Black Sea population, despite having a unique haplotype composition (Nh = 4), displayed moderate nucleotide diversity (π = 0.001411), whereas the Aegean and Antalya Bay populations showed intermediate diversity levels (π = 0.001791 and 0.001817, respectively).

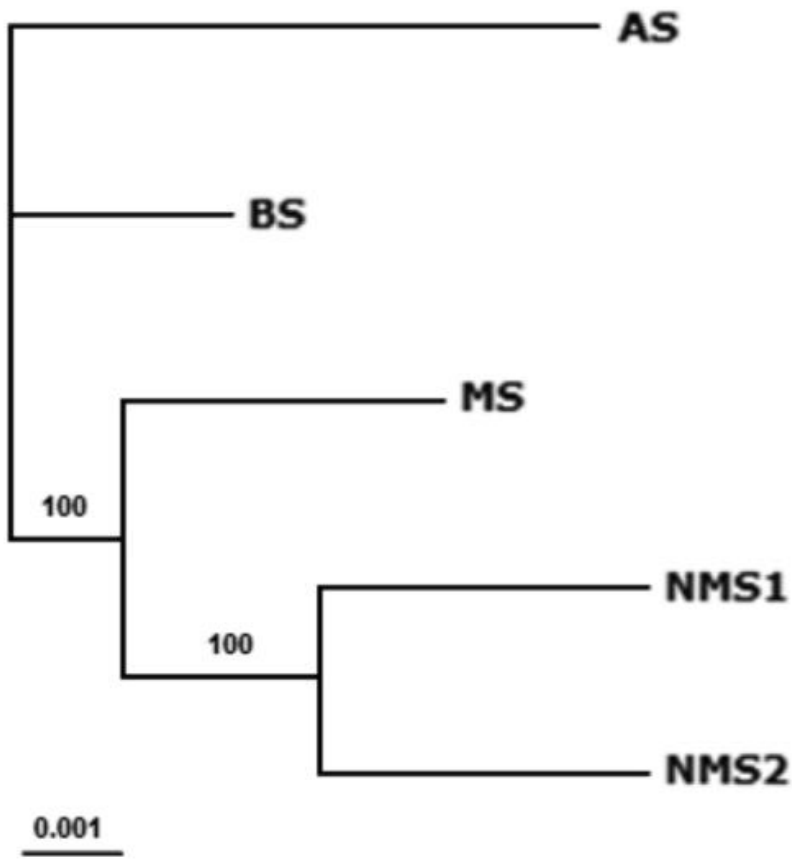

Figure 2. Neighbour-joining (NJ) tree showing the genetic relationships among *Chelidonichthys lucerna* populations from Turkish marine waters, based on mtDNA 16S rRNA sequences. Abbreviations: BS, Black Sea (Düzce); MS, Sea of Marmara; AS, Aegean Sea (İzmir Bay); NMS1, Northeastern Mediterranean (Antalya Bay); NMS2, Northeastern Mediterranean (İskenderun Bay). (Adapted from Uyan & Turan, 2017).

The phylogenetic clustering (Figure 2) places Antalya Bay (NMS1) and İskenderun Bay (NMS2) together, supporting a closer evolutionary history between these two northeastern Mediterranean populations, while the Aegean Sea population (AS) appears more genetically isolated. Pairwise genetic distances revealed that the lowest divergence was between the Black Sea and İskenderun Bay populations (0.001081), while the highest was between the Sea of Marmara and Antalya Bay (0.002067). Notably, statistically significant differentiation ($P < 0.05$) was found between the Marmara population and both the Aegean and Antalya Bay populations (Uyan & Turan, 2017). This pattern indicates restricted gene flow, likely driven by oceanographic barriers and limited larval dispersal, with the Dardanelles Strait acting as a primary barrier between the Black/Marmara seas and the Aegean/Mediterranean basins

Table 1. Genetic diversity metrics for *Chelidonichthys lucerna* populations across Turkish marine waters based on mtDNA 16S rRNA sequences. π: nucleotide diversity; N: sample size; Nh: number of haplotypes.

Population	Region	N	Nh	Nucleotide Diversity (π)
Black Sea (Düzce)	Black Sea	25	4	0.001411
Sea of Marmara	Marmara	25	5	0.001858
Aegean Sea (İzmir)	Aegean	25	5	0.001791
Antalya Bay	Mediterranean	25	5	0.001817
İskenderun Bay	Mediterranean	25	3	0.000462

(Data compiled from Uyan & Turan, 2017)

Pairwise genetic distances revealed that the lowest divergence was between the Black Sea and İskenderun Bay populations (0.001081), while the highest was between the Sea of Marmara and Antalya Bay (0.002067). Notably, statistically significant differentiation ($P < 0.05$) was found between the Marmara population and both the Aegean and Antalya Bay populations (Uyan & Turan, 2017). This pattern indicates restricted gene flow, likely driven by oceanographic barriers and limited larval dispersal. The neighbor-joining tree further supported this, showing the two northeastern Mediterranean populations (Antalya and İskenderun) clustering together, while the Aegean population appeared most isolated.

3.2 The Dardanelles Strait as a Phylogeographic Barrier

The pronounced differentiation of the Marmara Sea population is consistent with the role of the Dardanelles Strait system as a significant barrier to gene flow between the Black Sea and the Aegean Sea. This strait has been documented as a biogeographic boundary for several other Mediterranean marine species, including the European anchovy (*Engraulis encrasicolus*; Ivanova & Dobrovolov, 2006), Mediterranean horse mackerel (*Trachurus mediterraneus*; Turan et al., 2009), and Atlantic bonito (*Sarda sarda*; Turan, 2015). The Dardanelles likely restricts dispersal by creating hydrological discontinuities (salinity, temperature, and current regimes) that limit the exchange of eggs, larvae, and adults. The genetic isolation of the Marmara population of *C. lucerna* underscores its importance as a distinct management unit (MU).

3.3 Demographic History and Signals of Bottleneck

Tajima's D test for *C. lucerna* populations yielded a negative value (–1.703976), indicating an excess of rare alleles (Uyan & Turan, 2017). This signature is consistent with either a recent population expansion following a bottleneck or a selective sweep. Given the known history of intense fishing pressure in Turkish waters, particularly in the northeastern Mediterranean, a bottleneck scenario is plausible. Overfishing can drastically reduce effective population size, leading to the loss of rare alleles and a reduction in genetic diversity. Similar findings have been reported for other overexploited marine fishes, such as the spinner shark (*Carcharhinus brevipinna*; Geraghty et al., 2013). The extremely low diversity in İskenderun Bay ($\pi = 0.000462$) strongly suggests that this population has experienced a severe demographic contraction, likely due to a combination of fishing pressure, pollution, and climate change (Kocak et al., 2010; Yemisken et al., 2014).

3.4 Broader Phylogeographic Context and Knowledge Gaps

Outside of Turkish waters, phylogeographic data for gurnards are scarce. The only comparable study, conducted in the Adriatic Sea, also used 16S rRNA to resolve Triglidae phylogeny and recovered similar clades, although some population-level relationships differed (Riccioni et al., 2017). The limited geographic scope of existing studies precludes a comprehensive understanding of the historical biogeography of Mediterranean gurnards. The Siculo-Tunisian Strait, known to be a breakpoint for gene flow in other demersal fishes (Mejri et al., 2009), has not been investigated for gurnards. Similarly, the roles of Pleistocene glacial refugia and postglacial recolonization routes remain entirely unknown. A pan-Mediterranean phylogeographic study, incorporating samples from the western Mediterranean and Atlantic populations, is urgently needed to fill these gaps and to assess the genetic connectivity of gurnard species across their entire distribution range.

4. Current Conservation Status and Anthropogenic Threats

4.1 Regional Extinction of *Chelidonichthys obscurus*

The most alarming conservation finding is the likely regional extinction of the longfin gurnard, *Chelidonichthys obscurus*, from Turkish Mediterranean and Aegean waters. Despite being listed in historical checklists (Akışray, 1987), no specimens of this species have been captured or observed over the past three decades, despite extensive field surveys, interviews with fishermen, and communications with experienced scientists (Turan et al., 2016). This absence strongly suggests that the species is critically endangered or regionally extinct along the Turkish coasts.

Interestingly, *C. obscurus* has reappeared in the western English Channel between 2004 and 2013, where 82 specimens were recorded (Gary & Ellis, 2014), indicating that its disappearance from Turkish waters may be due to local environmental pressures rather than a global decline. The primary drivers are likely a combination of intensive bottom trawling, habitat degradation, pollution, and the effects of climate change and Lessepsian migration—the influx of Indo-Pacific species through the Suez Canal, which has significantly altered Mediterranean ecosystems over the past two decades (Turan, 2010; Turan et al., 2024). The species is recommended for listing as **Critically Endangered** (CR) in the Turkish Mediterranean and **Endangered** (EN) in the broader Mediterranean under the IUCN Red List (Turan et al., 2016).

4.2 Overfishing, Pollution, and Climate Change as Drivers of Genetic Erosion

The low genetic diversity observed in the İskenderun Bay population of *C. lucerna* serves as a stark warning of the combined effects of anthropogenic stressors. The northeastern Mediterranean is subject to intense fishing pressure, with nearly one hundred trawlers operating annually in the region (Yemisken et al., 2014). Additionally, the bay receives significant pollution loads from industrial complexes (steel, fertilizer, soda, glass, paper, and textile plants) and untreated municipal waste from major cities via the Asi River (Kocak et al., 2010). Furthermore, sea surface temperatures have been rising progressively over the past four decades, impacting biodiversity and ecosystem functioning (Turan et al., 2024). The combination of these factors has likely led to a demographic bottleneck, reducing effective population size and genetic diversity, which in turn diminishes the species' adaptive potential to future environmental changes (Allendorf et al., 2008).

4.3 Management Implications and Conservation Recommendations

The genetic and phylogeographic data reviewed here provide a scientific basis for evidence-based fisheries management:

Management Units (MUs)

The Sea of Marmara population of *C. lucerna* represents a distinct genetic unit and should be managed separately from Aegean and Mediterranean populations to prevent overfishing and preserve regional genetic integrity. Similarly, the highly vulnerable İskenderun Bay population requires enhanced protection, possibly through seasonal fishing closures and reduced trawling effort.

Species-Specific Measures

The regional extinction of *C. obscurus* underscores the need for urgent monitoring. eDNA (environmental DNA) surveys should be employed to confirm its absence and to detect any potential remnant populations. Additionally, efforts to reduce bycatch of non-target gurnard species should be prioritized through gear modifications.

Ecosystem-Based Management

Given that pollution and climate change are significant drivers of population decline, integrated coastal management strategies that address water quality, habitat restoration, and carbon emissions reduction are essential complements to fisheries regulations.

International Cooperation

As a shared resource, Mediterranean gurnard populations would benefit from collaborative management and research across national boundaries, ensuring data harmonization and coordinated conservation efforts under the framework of the General Fisheries Commission for the Mediterranean (GFCM).

Future Research Directions

While significant progress has been made, substantial knowledge gaps remain that must be addressed to ensure the long-term sustainability of gurnard populations:

Genomic-Scale Markers: Current studies rely primarily on mtDNA fragments. The application of next-generation sequencing (e.g., RAD-seq, whole-genome resequencing) is essential to resolve the paraphyly of *Chelidonichthys*, clarify the species boundaries of the *L. cavillone/L. dieuzeidei* complex, and identify adaptive loci under selection.

Pan-Mediterranean Sampling: Expanding sampling to include the western Mediterranean, Adriatic, Ionian, and Atlantic populations is critical to reconstruct historical biogeography, identify glacial refugia, and assess contemporary gene flow.

Population Connectivity: Integrating genetic data with oceanographic models (e.g., Lagrangian particle tracking) can elucidate larval dispersal pathways and identify barriers to gene flow, thereby informing the design of marine protected areas (MPAs).

Adaptive Genomics and Climate Change: Genome-environment association studies can reveal loci associated with temperature, salinity, and oxygen tolerance, predicting species' vulnerability to climate change and guiding assisted migration or selective breeding if necessary.

Historical DNA: Museum specimens of *C. obscurus* and other gurnards could provide temporal baselines for assessing genetic erosion and population declines over the past century (i.e., retrospective genomics).

Integrative Taxonomy: A comprehensive taxonomic revision of Mediterranean Triglidae, combining molecular phylogenetics, morphological analyses, and ecological data, is long overdue and would provide a stable foundation for conservation and management.

6. Conclusion

This review synthesizes the current state of knowledge on the molecular phylogeny, phylogeography, and conservation status of gurnard species (Triglidae, Dactylopteridae, Peristedidae) in the Mediterranean, with particular emphasis on Turkish marine waters. Our major conclusions are:

Phylogenetic structure: Triglidae is monophyletic, but the genus *Chelidonichthys* is paraphyletic due to the unstable placement of *C. cuculus*, which clusters with *E. gurnardus* and *T. lyra*. The species pair *L. cavillone* and *L. dieuzeidei* shows extremely low genetic divergence, requiring further taxonomic scrutiny.

Phylogeography: *C. lucerna* populations exhibit significant genetic structuring, with the Sea of Marmara representing a distinct genetic unit and İskenderun Bay showing alarmingly low genetic diversity, likely due to anthropogenic pressures.

Conservation crisis: *C. obscurus* is probably regionally extinct in Turkish waters, highlighting the vulnerability of gurnards to overfishing, pollution, and climate change.

Integrative approaches: Morphological and molecular data are only partially congruent, emphasizing the need for integrative taxonomy to accurately define species and population units.

Addressing the knowledge gaps identified herein through genomic approaches, expanded geographic sampling, and interdisciplinary collaboration will be crucial for the sustainable management and conservation of these ecologically and economically significant fishes in the rapidly changing Mediterranean Sea.

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Chapter 2

Analysis of the Factors Affecting the Climate Change Knowledge Level of Farmers in Sheep Enterprises

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Abstract

The main purpose of the study is to analyze the climate change knowledge level of producers in sheep farms and the factors affecting it. The sampling volume of the study was calculated as 151 according to the stratified random sampling method. The research area, Konya, is one of the driest provinces in Turkey, where grain production and sheep breeding are the predominant activities in the agricultural activities. The number of people who had heard about climate change in the research area was 69.54%, and multiple linear regression analysis was performed to analyze the factors affecting the climate change knowledge level of farmers. As a result, it was determined that education, professional experience, number of animals, land availability, and total labor potential were effective on the climate change knowledge level of the farmers and these factors were found statistically significant. The perception of climate change and the level of knowledge of sheep farmers were found to be important in terms of creating strategies for farmers to adapt to climate change.

Keywords: Climate change, Sheep farms, Level of knowledge, Konya, Turkey

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Introduction

According to the IPCC report, climate change is defined as long-term changes in weather conditions that persist for a statistically long time (IPCC, 2012). Climate change affects the world in different ways, including rising temperatures, droughts, heat waves, melting glaciers, rising sea levels, and floods (Mahmood et al., 2021). The effects are felt more severely in developing regions of the world, including Asian and African countries (Mahmood et al., 2021; IFAD, 2010). Climate change negatively affects agriculture and society and causes global warming (Umer Arshad et al., 2022). Environmental, economic, and social effects are observed in various sectors, especially in agriculture (Fierros-Gonzalez and Lopez-Feldman, 2021; Foguesatto and Machado, 2021; Panhwar Ghulam, 2024). Agricultural production provides the production of products necessary for people to continue their vital activities (Tosun and Oğuz, 2021). Climate change is a global threat to Earth. Livelihoods in rural areas depend heavily on agriculture and related industries, and so they are strongly affected by climate change (Ghalibaf et al., 2023). Yield fragility in agricultural production due to climate change is getting worse day by day (Waggoner, 1983; Smith et al., 1996; Adams et al., 1998; Hall et al., 2006; Tebaldi and Lobell, 2008; Nelson et al., 2009; Maleksaeidi and Karami, 2012; Agovino et al., 2019). It is projected that until the mid-21 st century, climate change will continue to negatively affect food security in the world. The majority of people with food insecurity live in South Asian countries (Hijioka, 2014). It is important to understand people's perceptions of global climate change and to determine the level of knowledge of rural farmers about climate change (Hansen et al., 2004; Silvestri et al., 2012; Imran et al., 2018; Niang et al., 2014; Matos Carlos et al., 2020; Oğuz et al., 2024). For this reason, analysing the climate change knowledge level of producers in sheep farms and the factors influencing it is impotant for developing effective adaptation strategies.

Material and method

Konya province, which is in second place in terms of sheep presence the research area and the driest region of Turkey, has been selected (TURKSTAT, 2023; Meteorology, 2023). The main material of the research was the primary data collected from the sheep farms of Konya through a questionnaire. The surveys were conducted between December 2021 and April 2022. In determining the main framework of the research, the records of the Konya Province Sheep and Goat Breeders' Association were used. The total number of sheeps in Konya is 2,769,018 head, and Karapınar, Ereğli, Cihanbeyli, Meram, Karatay, and

Çumra counties constitute 54.92% of the total sheep wealth in Konya (TURKSTAT, 2023). Therefore, these districts formed the main framework of the research. The sample volume was calculated as 151 using the following formula according to the Neyman method, one of the stratified random sampling methods, with a 5% margin of error in the 95% confidence interval (Yamane, 1967)

$$n = \frac{\sum (Nh.Sh)^2}{N^2.D^2 + \sum Nh.(Sh)^2} \qquad D^2 = (\frac{d}{t})^2$$

In the formula;

n: number of samples,

N: Number of enterprises in the main population,

Nh: Number of enterprises in the h layer (frequency),

Sh: standard deviation of the h layer,

d: Allowable margin of error from the population mean,

t: is the t table value corresponding to the 95% confidence interval predicted in the research.

The sample volume was divided into 3 layers according to the coefficient of variation. The survey was conducted with a total of 151 farms of which 22 are enterprises with 1-100 head of sheep in the 1st layer, 79 are enterprises with 101-250 head of sheep in the 2nd layer, and 50 are enterprises with 251+ head. When calculating the workforce in the examined enterprises as Man Power Units (MPU), the workforce in the 7-14 age group was calculated by multiplying with a coefficient of 0.50, the workforce in the 15-49 age group with a coefficient of 1.00 for men and 0.75 for women, and the workforce in the age group 50 and over with a coefficient of 0.75 for men and 0.50 for women (Erkuş, 1995), Considering the natural conditions of the research area, it has been accepted that it can work 280 days a year in plant production and 300 days in animal production. The days when it is not possible to actually work, such as continuous illness, military service, and education, are excluded from the potential workforce values. Thus, the number of days worked was multiplied by the coefficients (MPU) for each age group and gender and converted into Male Workdays (MWD) (Erkuş, 1995; Peker, 1997).

Farmers' views on the environmental, plant, animal, economic, and social effects of climate change in sheep holdings in the last 20 years were obtained with 3-point Likert questions. The factors in question were scored as: 1- increased, 2- decreased, and 3- unchanged, and their averages were taken to create the climate change knowledge index (CCKI) for sheep holdings. For the index, 18 factors were used: drought/desertification, wind, sinkhole formation, afforestation activities, forest fires, greenhouse gas emissions, diseases and pests in crop production, animal deaths, diseases and pests in sheep and goat farming, input costs, product market, unemployment due to production change, migration, poverty, and farmer income. Multiple linear regression analysis was also conducted to analyze the factors affecting the climate change knowledge level of farmers (Fox, 1997; Kalaycı, 2005; Anonymous, 2006; Topçu 2008). The SPSS-24 statistical software package was used to solve the model (Tümer and Birinci, 2011). The simple linear regression equation for the population to show the dependent variable Y, the independent variable Xi, the unknown parameter β1 of this variable, and the unobservable error terms εi is as follows:

$Y = \beta + \beta Xi + \varepsilon, i = 1,2,...,n.$

In the study, dependent and independent variables were taken as follows:

Y= Climate change knowledge index of sheep breeding enterprises (CCKI)

X_1= Farmer income, X_2= Professional experience (years), X_3= Total workforce (MPU), X_4= Number of animals (head), X_5= Education, X_6=Total land assets (decares), X_7=Farmer's age (years)

Research findings

Statistical information on the socio-economic structure of enterprises

There are studies in the literature on how social and economic factors can be affected by climate change (Rosenzweig & Willbanks, 2010; Lal et al., 2011). Considering the age status of the enterprises, the active population of the 15-49 age group is quite high in the 1st group, 2nd group, and 3rd group enterprises (Table 1).

Table 1. Distribution of the population in sheep farms by age and education level (Number, %)

		1-100		101-250		251+		Enterprises average	
		Number	%	Number	%	Number	%	Number	%
Age	0-6	0.45	10.20	0.14	3.32	0.32	6.61	0.25	5.62
	7--14	0.81	18.37	0.64	15.17	0.44	9.09	0.60	13.48
	15-49	2.00	45.35	2.28	54.03	2.64	54.55	2.35	52.81
	50-+	1.14	25.85	1.16	27.49	1.44	29.75	1.25	28.09
	Total	4.41	100.00	4.22	100.00	4.84	100.00	4.45	100.00
Education	Illiterate	0.55	12.47	0.27	6.40	0.32	6.64	0.32	7.21
	Literate	0.09	2.04	0.06	1.42	0.08	1.66	0.07	1.58
	Primary Education	2.86	64.85	2.87	68.01	3.38	70.12	3.04	68.47
	High School	0.73	16.55	0.75	17.77	0.56	11.62	0.68	15.32
	College	0.09	2.04	0.06	1.42	0.20	4.15	0.11	2.48
	Bachelor's	0.09	2.04	0.19	4.50	0.28	5.81	0.21	4.73
	Post-graduate	0.00	0.00	0.01	0.24	0.00	0.00	0.01	0.23
	Total	4.41	100.00	4.22	100.00	4.82	100.00	4.44	100.00
Land Assets (da)	Total	222.48		166.37		585.84		313.44	
Sheep presence (head)	Total	79.95		323.05		990.34		508.59	
Family workforce potential	MWD	862.50		926.58		1062.00		962.09	

The economic terms, the active population refers to those actually angaged in agricultural labor. Therefore, the active population is defined as all persons engaged in economic activity or seeking employment in a family business as employers, self-employed, salaried, or unpaid workers (Bagchi et al., 2019). Considering the educational status of enterprises, the proportion of primary school graduates is relatively high in all three enterprise groups. The land assets of the enterprises are 313.44 decares on average and the land assets of the 3rd group enterprises are more than those of the other enterprises with 585.84 decares. A large amount of cultivated land is important in terms of feed production, especially in small cattle breeding enterprises. In terms of sheep assets, there is an average of 508.59 head of livestock. Family labor potential is important and it is 962.09 male working days on average in the enterprises.

Climate change knowledge levels of sheep farmers

In the research area, farmers' perceptions of climate change in sheep farms affect not only planting decisions but also climate change adaptation measures (Hansen et al., 2004; Silvestri et al., 2012; Meldrum et al., 2018; De Matos Carlos et al., 2020). Therefore, farmers' knowledge of climate change is very important. How sheep farms perceive and define climate change is important and is given in Table 2. According to the table, the number of people hearing about climate change in sheep farms is 105 in total, which constitutes 69.54% of the total farms. 30.46% of businesses have no knowledge about climate change. Those who define climate change as sudden weather changes are 38 people and they constitute 25.17% of the total enterprises. Those who interpret it as the change of seasons are determined as 41.06%, those who define it as human-caused pollution as 17.88%, those who define it as extreme heat, drought, and global warming as 46.36%, those who define it as greenhouse gas emissions as 9.93%, and those who describe it as the occurrence of disasters as 8.61%.

Table 2. Farmers' definitions of climate change

Identification states	Number	%	Total
Number hearing about climate change	105.00	69.54	151
Sudden weather changes	38.00	25.17	151
Change of seasons	62.00	41.06	151
Pollution of nature caused by man	27.00	17.88	151
Extreme heat, drought, and global warming	70.00	46.36	151
Greenhouse gas emissions	15.00	9.93	151
Occurrence of disasters	13.00	8.61	151

The opinions of the farmers about the climatic changes in the last 20 years are scored and given in Table 3. Farmers 95.37% stated that the temperature had increased in the research area in the last 20 years, 91.67% of them stated that drought and desertification had increased, and 76.85% of them stated that the formation of sinkholes had increased. 88.89% of the producers stated that the living areas of animals had decreased with climate change, 91.67% of them stated that water resources had decreased and groundwater was withdrawn, 91.67% of them stated that input costs had increased, 67.59% stated that farmers' incomes had decreased, 74.07% of them stated that diseases and pests in sheep breeding had increased, 75.93% stated that forest fires had increased, and 45.37% of them stated that afforestation works had increased.

Table 3. Farmers' views on the effects of climate change over the last 20 years

Factors	3	%	2	%	1	%	Average
Heat	-	-	5	4.63	103	95.37	1.05
Drought / desertification	3	2.78	6	5.56	99	91.67	1.11
Forest fires	19	17.59	7	6.48	82	75.93	1.42
Sink formation	23	21.30	2	1.85	83	76.85	1.44
Wind	21	19.44	7	6.48	80	74.07	1.45
Greenhouse gas emissions	33	30.56	6	5.56	69	63.89	1.67
Afforestation activities	26	24.07	33	30.56	49	45.37	1.79
Precipitation regime	2	1.85	89	82.41	17	15.74	1.86
Biodiversity	29	26.85	40	37.04	39	36.11	1.91
Water resources (groundwater etc.)	4	3.70	99	91.67	5	4.63	1.99
Natural habitats of animals	6	5.56	96	88.89	6	5.56	2.00
Diseases and pests in crop production	6	5.56	5	4.63	97	89.81	1.16
Animal mortality	18	16.67	15	13.89	75	69.44	1.47
Diseases and pests in sheep farming	9	8.33	19	17.59	80	74.07	1.34
Input costs	1	0.93	8	7.41	99	91.67	1.09
Unemployment due to change in production	29	26.85	24	22.22	55	50.93	1.76
Migration events	29	26.85	14	12.96	65	60.19	1.67
Farmer income	6	5.56	73	67.59	29	26.85	1.79

(1-increased 2- decreased 3- unchanged)

by Farmers' views on the effects of climate change on crop production in the last 20 years are given in Table 4. In the research area, 43 of 151 enterprises stated that they did not have information about climate change. 108 of the enterprises expressed their opinions about the changes in crop production due to climate change in the last 20 years.

Table 4. Farmers' views on the effects of climate change on crop production in the last 20 years

Factors	3	%	2	%	1	%	Average	Total	%
Diseases and pests in crop production	6	5.56	5	4.63	97	89.81	1.16	108	100
Number of crops planted	12	11.11	31	28.70	65	60.19	1.51	108	100
Unconscious irrigation	11	10.19	40	37.04	57	52.78	1.57	108	100
Efficiency in plant production	5	4.63	66	61.11	37	34.26	1.70	108	100
Product quality in plant production	10	9.26	67	62.04	31	28.70	1.81	108	100

(1-increased 2- decreased 3- unchanged)

According to the table 4, 89.81% of the farmers stated that diseases and pests had increased in plant production, 60.19% stated that the number of products grown had increased, 62.04% stated that the product quality had decreased and 61.11% stated that there were significant decreases in yield. Views of farmers on the effects of climate change on animal production in the last 20 years in the research area are given in Table 5.

Table 5. Farmers' views on the effects of climate change on animal production in the last 20 years

Factors	3	%	2	%	1	%	Average	Total	%
Diseases and pests in sheep farming	9	8.33	19	17.59	80	74.07	1.34	108	100
Animal mortality	18	16.67	15	13.89	75	69.44	1.47	108	100
Number of animals	7	6.48	44	40.74	57	52.78	1.54	108	100
Quality in sheep farming products	14	12.96	47	43.52	47	43.52	1.69	108	100
Yield in sheep	12	11.11	53	49.07	43	39.81	1.71	108	100
Pasture fields	9	8.33	83	76.85	16	14.81	1.94	108	100

(1-increased 2- decreased 3- unchanged)

According to the table, 74.07% of the farmers stated that diseases and pests in sheep farming had increased due to climate change in the last 20 years, 76.86% of them stated that pasture areas had decreased (human activity-oriented), 69.44% of them stated that animal deaths had increased, and 52.78% of them stated that the number of animals had increased. Although there are human-induced reductions of pasture areas, the effects of climate change are also effective in the reduction of pasture areas. The existence of pasture areas is especially important in small cattle breeding. According to the data of the Turkish Statistical Institute (TURKSTAT), there are 14.6 million hectares of meadows and pastures, which is approximately 20 percent of the country's total area and 38 percent of the agricultural land. Although pasture areas are shrinking every year, the quality of 20 thousand hectares of pasture area has changed in the last 5 years. Conservation of pasturelands is not only for feeding animals and forage crop production; it is also necessary to attach great importance to pastures for the protection of natural resources and sustainable agricultural production. However, while the meadow-pasture area in Turkey was 46 million hectares in 1928, it has decreased to less than 15 million hectares today (TURKSTAT, 2023). Views of farmers about the economic effects of climate change in the research area in the last 20 years are given in Table 6. According to this, 91.67% of the farmers stated that the input costs had increased a lot, accordingly, 67.59% of the farmers stated that the income of the producers had decreased, 60.19% of them stated that the product prices had increased, and 50.93% of them stated that unemployment in agriculture had increased due to the change in production.

Table 6. Farmers' views on the economic effects of climate change in the last 20 years

Factors	3	%	2	%	1	%	Average	Total	%
Input costs	1	0.93	8	7.41	99	91.67	1.09	108	100
Product prices	12	11.11	31	28.70	65	60.19	1.51	108	100
Unemployment due to change in production	29	26.85	24	22.22	55	50.93	1.76	108	100
Finding financial resources (loans, grants, etc.)	28	25.93	28	25.93	52	48.15	1.78	108	100
Farmer income	6	5.56	73	67.59	29	26.85	1.79	108	100
Product market	33	30.56	24	22.22	51	47.22	1.83	108	100

(1-increased 2- decreased 3- unchanged)

In the study, the social effects of climate change in the last 20 years are given in Table 7. According to the table, 69.44% of the farmers stated that the level of knowledge of the farmers on climate change had increased in the last 20 years, 66.67% of them stated that poverty had increased, 60.19% of them stated that migration events had increased, and 40.74% of them have stated that the quality of life and standard of living of the farmers had decreased.

Table 7. Farmers' views on the social impacts of climate change in the last 20 years

Factors	3	%	2	%	1	%	Average	Total	%
Farmers' level of knowledge on climate change	18	16.67	15	13.89	75	69.44	1.47	108	100
Poverty	19	17.59	17	15.74	72	66.67	1.51	108	100
Migration events	29	26.85	14	12.96	65	60.19	1.67	108	100
Farmers' quality of life and standard of living	23	21.30	44	40.74	41	37.96	1.83	108	100

(1-increased 2- decreased 3- unchanged)

In one study, it was determined that awareness of climate change is determinant in climate change risk perceptions (Zobeidi et al., 2020). As can be seen from the table, farmers' awareness of climate change has increased in the last 20 years.

Analysis of the factors affecting the climate change knowledge level of farmers

Multiple linear regression analysis for the analysis of the factors affecting the climate change knowledge levels of farmers is given in Table 8. In the regression model, the climate change knowledge index of the enterprises (CCKI) was taken as the dependent variable (Y).

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4X4 + \ldots\ldots\ldots + \beta 7X7$$

According to the results of the analysis, 6 out of 7 variables included in the model were found to be significant.

Table 8. Analysis of the factors affecting the climate change knowledge level of farmers

Model		Unstandardized Coefficients B	Std. Error	Beta	t	Sig.
1	(Constant)	-.174	.117		-1.490	.139
	Education (X1)	.249	.029	.351	8.471	.000***
	Professional experience (X2)	.032	.019	.083	1.673	.097*
	Number of animals (head) (X3)	.000	.000	.135	3.114	.002**
	Land assets (da) (X4)	.000	.000	.107	2.473	.015**
	Age	.001	.003	.023	.458	.648
	Total workforce (X5)	.000	.000	.109	2.704	.008**
	Farmer income (X6)	.650	.029	.847	22.298	.000***
	R^2=.895[a],	F=81.74 (0.009),		Durbin-	Watson=2.347	

*,**,*** P < 0.1, P < 0.05, P < 0.01 Predictors: (Constant), Education, Professional experience, Number of animals (head), Total land assets (da), Age, Total workforce (TWF), Farmer income. Dependent Variable: Climate change knowledge level (Y)

$$\mathbf{Y= -0.174 +0.249X_1+0.032X_2-0.000X_3+0.000X_4+0.000X_5+0.650X_6}$$

p sig. (0.000) (0.097) (0.002) (0.015) (0.008) (0.000)

As a result of the analysis, the explanatory power of the independent variables for the dependent variable (R^2), was calculated as 89.50%. This rate indicates the success of explaining the climate change knowledge level of farmers. F test was performed to determine whether the R^2 value was significant, and it was determined to be significant at the 1% significance level as a result of the test. Durbin-Watson (2.347) values were calculated to determine whether there was an autocorrelation and multicollinearity problem in the model and the model was accepted as statistically significant. As a result of the study, the signs of the coefficients of the independent variables were interpreted and their effects on the farmers' climate change knowledge levels were examined. Among the independent variables, education, number of animals, labor force, and farmer income were found to be statistically significant at the 1% significance level. A positive relationship was determined between education and climate change knowledge level. That is, as the education level increases, there is an increase in the climate change knowledge level of the farmers. In other words, the level of perception of climate change by farmers with a high level of education is 0.249 times higher. As a matter of fact, Quddus (2017) determined that producers with a high level of education in Bangladesh were 9.7 times more likely to adopt innovations than illiterate producers. Again, at the level of 5% of the farmers' land assets and 10% of their professional experience, the animals of the farmers were found to be statistically significant.

Conclusion and recommendations

Climate is a key factor in agricultural production, making the sector highly vulnerable to climate change. In the study area, sheep farming is common, supported by pasture availability. While 69.54% of farmers were aware of climate change, most observed rising temperatures, increased drought, reduced water resources, and higher input costs. Factors such as education, income, experience, and herd size significantly influenced farmers' climate change awareness. Adapting to climate change is crucial for sustainable production. Education and socio-economic conditions shape farmers' perceptions and responses. Therefore, policy-makers should prioritize climate education, integrate climate topics into agricultural training, offer financial support to small ruminant farms, and provide mobile-based climate information to enhance farmers' adaptive capacity.

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Conflicts of Interest

The authors declare no conflict of interest.

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Chapter 3

The Use of Plant Tissue Cultures in Plant Breeding

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1. The Importance of Plant Breeding

Plant breeding is defined as a scientific process encompassing the creation, selection, and evaluation of genetic variation in plants to develop genotypes with superior economic, agronomic, and biological characteristics. Plants form the basic step of the food chain and directly or indirectly support the lives of all living things on Earth. Therefore, plant production and plant breeding have been among the fundamental issues that humanity has focused on throughout history.

However, plant production has still not reached a sufficient level in many countries worldwide. On the other hand, the world population was approximately 6.1 billion in 2000, reaching 7.2 billion in 2012, and is projected to reach approximately 8.3 billion by 2026. Currently, the annual world population growth rate is approximately 0.85%, and it is predicted that the world population will reach 9.7 billion in 2050 (Anon., 2026). This rapid population growth necessitates a continuous increase in agricultural production to meet the growing demand for food and other basic needs in a sustainable manner.

Many factors influence the increase in plant production, including the genetic potential of the plant, cultivation techniques, environmental conditions, and agricultural practices (Kurt, 2023). However, given the limited cultivated areas in today's conditions, the most effective way to increase production is to increase the yield per unit area. Achieving this depends primarily on improving the genetic potential of plants. At this point, developing new varieties that are high-yielding, high-quality, resistant to diseases and pests, and adaptable to changing climate conditions is of great importance. Plant breeding plays a strategic role in achieving these goals, ensuring sustainable agricultural production, and protecting global food security.

Thanks to plant breeding studies, which gained a scientific basis with the establishment of Mendel's principles of heredity, significant improvements have been achieved in the genetic potential of almost all cultivated plants grown today. When the average yield values of cultivated plants widely grown worldwide are

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examined, it is seen that the yield per unit area has increased by at least two to three times in many species (Table 1) (FAO, 2026). In addition to plant breeding studies, advancements in fertilization, plant protection practices, irrigation systems, mechanization, and other modern agricultural technologies have also played a significant role in this increase.

Table 1. Average yield increase values for some widely cultivated plants worldwide (FAO, 2026)

Plants	**Yield (kg per decare)**		**Change (Times)**
	1961	**2024**	
Wheat	108,9	363,7	3,3
Rice	186,9	475,7	2,6
Tomato	1643,5	3681	2,2
Apple	990,6	2089	2,1
Maize	194,2	580,2	3,0
Eggplant	886,6	2933,7	3,3
Soybean	112,9	277,8	2,5

However, the basis of the achieved yield increase is the genetic potential of the plant. Genetic potential is one of the most important factors determining the maximum yield level a plant can reach under suitable environmental conditions and optimum cultivation practices. For example, if it is assumed that one of two genotypes of the same species has a yield potential of 400 kg per decare and the other has a yield potential of 600 kg per decare; Even if both genotypes are provided with the same environmental conditions and the most suitable cultivation techniques (planting time, fertilization, irrigation, plant protection applications, etc.), a yield significantly above 400 kg per decare is not expected from the genotype with a genetic potential of 400 kg per decare. In contrast, the genotype with a genetic potential of 600 kg per decare can reach a yield level close to this value under suitable conditions.

This example clearly demonstrates how critical it is to improve genetic potential in increasing the amount of product obtained per unit area. Therefore, developing new varieties with superior genetic characteristics through plant breeding studies remains one of the fundamental goals of modern agriculture to ensure sustainable yield increases.

From the past to the present, classical plant breeding methods have made significant contributions to increasing plant production and improving agricultural productivity. Indeed, the high yields and quality levels achieved in many cultivated plants widely grown today are largely the result of classical breeding efforts carried out over many years. However, classical plant breeding methods are inherently time-consuming, and developing a new variety generally requires at least 8–10 years of work. This period can be even longer depending on the plant species being bred, the methods used, and the targeted characteristics.

Another significant limitation of classical breeding is that genetic variation is largely limited to the existing gene pool of the species. In other words, it is quite difficult, and often impossible, to introduce characteristics that are not naturally present or found in closely related species into cultivated plants using classical methods. This situation creates significant limitations, particularly in the development of many characteristics such as disease and pest resistance, abiotic stress tolerance, and quality traits.

Advances in plant biotechnology have significantly contributed to overcoming these limitations. Plant cell and tissue culture techniques have become one of the most important biotechnological tools that complement and enhance the effectiveness of traditional plant breeding. These techniques allow for the culturing of plant cells, tissues, and organs under controlled laboratory conditions, as well as enabling intervention in the genetic structure at the cellular level. Furthermore, these techniques allow for selection in the early generations of breeding programs, the faster acquisition of homozygous lines, the propagation of disease-free plants, and the implementation of biotechnological applications such as genetic transformation and somatic hybridization. In addition, the ability to transfer certain characteristics to plants through different biotechnological approaches that cannot be introduced into the gene pool by classical breeding methods further increases the strategic importance of cell and tissue culture techniques in plant breeding.

2. Cell and Tissue Culture Techniques Used in Plant Breeding

Plant cell and tissue culture techniques are biotechnological methods that allow the cultivation, multiplication, preservation, and, if necessary, modification of the genetic structure of plant organs, tissues, cells, and protoplasts in artificial culture media under sterile conditions (Hatipoğlu, 2012). Today, these techniques are among the fundamental biotechnological tools that not only enable the rapid multiplication of plants but also increase the effectiveness of classical plant breeding and eliminate many of its limitations.

Cell and tissue culture techniques allow for the rapid and high-volume multiplication of economically important plant species, accelerate the selection process in breeding programs, develop homozygous lines quickly, preserve genetic resources safely and economically for extended periods, develop interspecies and intergenera hybrids that are difficult to obtain with classical methods, transfer genetic material at the cellular and molecular level, and produce secondary metabolites under controlled laboratory conditions. Thanks to these features, cell and tissue culture techniques have become an indispensable component of modern plant breeding.

Cell and tissue culture techniques commonly used in plant breeding studies can be classified as follows (Hatipoğlu, 2012):

1. Clonal propagation (micropropagation)
2. Meristem culture
3. Somaclonal variation
4. Embryo culture
5. Haploid plant production
   - 5.1. Anther and microspore culture
   - 5.2. Ovule and ovary culture
   - 5.3. Embryo rescue (embryo culture) in hybrids between species and genera
6. *In vitro* pollination and fertilization
7. Protoplast culture and somatic cell hybridization
8. *In vitro* preservation of genetic material
9. Genetic transformation (gene transfer)

Appropriate physical infrastructure and technical equipment are necessary for the successful application of these techniques. First and foremost, a well-equipped plant tissue culture laboratory is needed, consisting of a preparation room, sterilization unit, aseptic work area (laminar flow cabinet), culture room, and climate control section, where sterile working conditions can be fully ensured. In addition, having technically trained and experienced personnel in cell and tissue culture is crucial for the correct application of methods and the achievement of successful results.

The success of cell and tissue culture studies depends on the genotype of the plant material used, the source and physiological state of the explant, the age and size of the explant, the composition of the culture medium in terms of mineral nutrients, vitamins, carbon source and plant growth regulators, and the environmental conditions of the culture medium such as temperature, light intensity, photoperiod and humidity. Since each of these factors directly affects the initiation, maintenance and regeneration success of the culture, determining the optimum conditions in tissue culture studies is of great importance.

2.1. Clonal Propagation (Micropropagation)

Clonal propagation, also known as micropropagation, is one of the most widely applied methods in plant cell and tissue culture techniques. Its basic principle is based on obtaining exact copies (clones) of the parent plant without altering its genetic structure, like classical vegetative propagation methods (cuttings, tubers, rhizomes, bulbs, grafting, etc.). However, this process is carried out in sterile culture media under controlled laboratory conditions, achieving a much higher reproduction rate compared to classical vegetative propagation.

In plant breeding, clonal propagation techniques are widely used, especially when the preservation of genetic structure is desired and when the aim is to quickly increase the number of genotypes with superior characteristics. It also plays an important role in many biotechnological applications such as the propagation of newly developed varieties, the preservation of elite genotypes, the production of transgenic plants, and the conservation of genetic resources.

The basis of the method is; The process involves transferring plant parts (explants) such as stems, shoot tips, nodes, leaves, roots, hypocotyls, cotyledons, etc., into artificial culture media under sterile conditions and ensuring the regeneration of new plants under suitable culture conditions. Explants used in culture can be obtained from aseptic seedlings produced from sterilized seeds, or from materials taken from naturally grown plants and subjected to surface sterilization.

Cultured explants can follow two different developmental pathways during regeneration. In the first pathway, direct organogenesis, new plants are formed by the development of shoots and then roots directly from the explant without any callus formation. In the second pathway, indirect organogenesis, the explant first forms callus, and then shoots and roots develop from this callus to obtain new plants. The direct regeneration method is preferred, especially in plant breeding studies, due to its lower risk of genetic modification.

The main advantages of clonal propagation techniques are summarized below:

i) It allows for the rapid propagation of a large number of plants in a small laboratory area.

ii) Production can be carried out year-round, regardless of climatic conditions.

iii) It provides a much higher propagation coefficient than traditional vegetative propagation methods.

iv) It enables the propagation of plant species that are difficult or slow to propagate vegetatively.

v) It ensures the production of genetically preserved, uniform, and high-quality plant material.

vi) It contributes to the rapid dissemination of superior genotypes in breeding programs.
vii) It can be used as an important step in the production of disease-free plant material.

However, the method also has some limitations and disadvantages:

i) A well-equipped tissue culture laboratory with sterile conditions is required for the studies to be carried out.
ii) The application of the method requires personnel experienced and trained in cell and tissue culture.
iii) There is no standard micropropagation protocol for every plant species. Therefore, it is necessary to develop culture media and culture conditions specific to the species and even genotype. Regular monitoring of *in vitro* cultures and prevention of contamination require intensive labour and attention. Ensuring surface sterilization can be particularly challenging in explants taken from underground organs (bulbs, tubers, rhizomes, etc.).
iv) Some plant species or genotypes show a low regeneration response to *in vitro* culture conditions.
v) Adaptation of plantlets removed from the culture medium to the external environment (acclimatization) is difficult in some species, and significant losses can occur at this stage.
vi) In long-term subcultures, especially in systems where the callus phase is present, somaclonal variation can occur, negatively affecting the preservation of genetic purity.

In conclusion, clonal propagation is one of the most widely used cell and tissue culture techniques in plant breeding and commercial seedling production because it allows for the rapid and high-number propagation of superior genotypes. Its high propagation capacity, especially in cases where preserving genetic structure is important, has made the method an indispensable application of modern plant biotechnology.

2.2. Meristem Culture

Meristem culture is a cell and tissue culture technique that involves isolating shoot tip meristems, where active cell division occurs in plants, under sterile conditions, culturing them in artificial culture media, and regenerating new plants from these tissues. These growth cones, also called apical meristems, consist of undifferentiated cells capable of continuous division and are the fundamental tissues responsible for the plant's primary growth.

Because meristem tissue is a relatively small structure, its isolation requires technical skill. Furthermore, due to the limited number of meristems that can be obtained from a single plant, in practice, shoot tips containing meristems, as well as axillary or dormant buds, are often used as explants. This facilitates the initiation of culture and increases regeneration success.

Meristem culture is one of the most widely used methods in plant breeding and seedling production, particularly for obtaining virus-free plant material. Although many plant viruses are transported within the plant via vascular bundles, they either do not reach the meristem region where rapid cell division occurs or are found there in very low concentrations. Therefore, virus-free plants can often be obtained from meristems isolated from infected plants. If necessary, this success rate can be further increased by applying meristem culture in conjunction with adjuvant methods such as thermotherapy, chemotherapy, or cryotherapy.

Plants obtained through meristem culture do not acquire resistance to viruses. This method only allows to produce virus-free individuals from a virus-infected parent plant. Therefore, these plants can become infected again if they are subsequently exposed to viral agents. For this reason, taking preventative measures against reinfection during the production and cultivation process of the resulting healthy material is of great importance.

Another important advantage of meristem culture is that regeneration mostly occurs directly through organogenesis, and callus formation is absent or very limited. Eliminating the callus phase significantly reduces the risk of somaclonal variation, contributing to the preservation of genetic stability in the resulting plants. This feature is of great importance, especially for the propagation of superior genotypes, breeding lines, and commercial varieties without altering their genetic structure.

The main advantages of meristem culture are summarized below:

It ensures the production of virus-free and healthy plant material.

i) It allows for a high degree of genetic preservation.
ii) The risk of somaclonal variation is low due to limited callus formation.
iii) It enables the safe propagation of superior genotypes.
iv) It provides clean starting material for many species that are difficult to propagate by seed or are produced vegetatively.

However, the method also has some limitations:

i) Due to the very small size of meristem tissue, its isolation is difficult and requires advanced technical expertise.

ii) The number of meristems that can be obtained from a single plant is limited.
iii) Not every plant species and genotype respond to meristem culture with the same success.
iv) It requires special laboratory infrastructure and sterile working conditions.
v) Although it eliminates the virus, it does not confer virus resistance on plants.

In conclusion, meristem culture is one of the most important applications of plant biotechnology in terms of preserving genetic structure and especially obtaining virus-free starting material. It is widely used in fruit species, ornamental plants, potatoes, bananas, strawberries, garlic, and many other vegetatively propagated crops; and constitutes one of the fundamental steps in certified seedling and sapling production systems.

2.3. Somaclonal Variation

In vitro propagation techniques are basically among the vegetative propagation methods, and the aim of these methods is to obtain clonal individuals without changing the genetic structure of the parent plant. Therefore, under normal conditions, genetic stability is expected to be preserved in plants obtained because of *in vitro* regeneration. However, the morphological, physiological, cytological and molecular differences observed especially in plants obtained through regeneration from callus cultures have revealed that the genetic structure is not always fully preserved in *in vitro* cultures. This phenomenon was described systematically for the first time and was called somaclonal variation (Lörz, 1985).

Somaclonal variation is the general name for hereditary or non-heritable changes that occur during *in vitro* culture of plant cells, tissues or organs. These changes can occur because of various mechanisms such as chromosomal rearrangements, gene mutations, ploidy changes, transposon activation and differences in DNA methylation. While some of the resulting variations are genetically based and can be transferred to subsequent generations, some of them result from epigenetic changes caused by environmental or cultural conditions. Epigenetic changes do not cause any changes in the DNA sequence and are often not permanent and are not transmitted to subsequent generations (George, 1993; Karp, 1994).

Many factors are effective in the emergence of somaclonal variation in *in vitro* culture. The most important of these are plant species and genotype, explant type, culture duration, number of subcultures, composition of the medium used, and especially the type and concentration of plant growth regulators. Adding high doses of auxin to the medium or using auxin and cytokinins at rates that will promote callus formation promotes callus formation by increasing the dedifferentiation of cells and, accordingly, significantly increases the frequency of somaclonal variation (Hatipoğlu, 2012; Uysal, 2021). For this reason, the possibility of variation in indirect regeneration systems that include the callus phase is much higher than in regeneration carried out directly through organogenesis.

Culture duration is also an important factor in the formation of somaclonal variation. During long-term cultures and successive subcultures, the possibility of accumulation of chromosomal irregularities and genetic changes in cells increases. For this reason, it is recommended to keep the number of subcultures as low as possible to preserve genetic stability, especially in micropropagation studies.

When evaluated in terms of plant breeding, somaclonal variation is considered both a disadvantage and an important source of genetic variation. Since the aim of micropropagation studies is to reproduce superior genotypes exactly, the resulting variations are undesirable. On the other hand, somaclonal variation can provide a significant advantage in breeding programs that aim to create new genetic variation. Beneficial mutations that occur during *in vitro* culture can be selected and used to develop new genotypes. With this method, many successful studies have been carried out to improve quality characteristics and resistance to diseases and pests, herbicide tolerance, resistance to abiotic stress factors such as salinity, drought, high or low temperature.

One of the important advantages of somaclonal variation studies is that they can be applied together with *in vitro* selection. By adding certain selection factors (such as salt, heavy metals, toxins, herbicides, pathogen toxins or compounds that mimic drought stress) to the culture medium, the development of only resistant cells can be ensured. Later, the plants obtained from these cells through regeneration can be included in plant breeding programs as materials that have undergone pre-selection for the desired characteristics. Thus, selection processes that are difficult or take a long time to carry out under field conditions can be carried out in a more controlled, faster and economical way in the laboratory environment.

As a result, although somaclonal variation is a phenomenon that needs to be controlled in micropropagation studies that aim to preserve genetic stability, it is considered an important source of mutation and selection in plant breeding programs that aim to create new genetic variation. For this reason, today, somaclonal variation has become one of the important biotechnological approaches widely used in modern plant biotechnology and plant breeding to both increase genetic diversity and develop new genotypes resistant to stress conditions.

2.4. Embryo Culture

Embryo culture is a cell and tissue culture technique that allows mature or immature zygotic embryos in the seed to be isolated under aseptic conditions and cultured in artificial media and to obtain plants that have completed normal development from these embryos. Embryo culture, one of the oldest and most widely applied methods in plant biotechnology, provides significant advantages, especially in plant breeding, in terms of increasing hybridization success and shortening the generation period.

Embryo culture is divided into two groups: mature embryo culture and immature embryo culture, depending on the development period of the embryo used. Mature embryo culture is mostly applied to eliminate seed dormancy and to obtain rapid seedlings in species that have difficulty germinating. Isolating the embryo from seeds that do not germinate for a long time under normal conditions due to dormancy and placing them in a suitable nutrient medium significantly shortens the germination period by allowing the embryo to develop without being affected by the dormancy barrier. This technique is widely used in many plant species, especially fruit species, forestry plants and those with hard-shelled seeds. Immature embryo culture is commonly called embryo rescue technique. This method is especially applied in cross-breeding between species and genera, in cases where, although fertilization occurs, the embryo undergoes degeneration before completing its normal development. In this type of crossbreeding, the embryo may lose its viability in the early period due to reasons such as inadequate development of the endosperm or embryo-endosperm incompatibility. When the embryo is isolated under sterile conditions before degeneration and cultured in a suitable medium, it can complete its development and viable hybrid plants can be obtained (Uysal et al., 2007) (Figure 1). For this reason, the embryo rescue technique is used as an important biotechnological tool in the development of many distant hybrids that are not possible to obtain by classical methods.

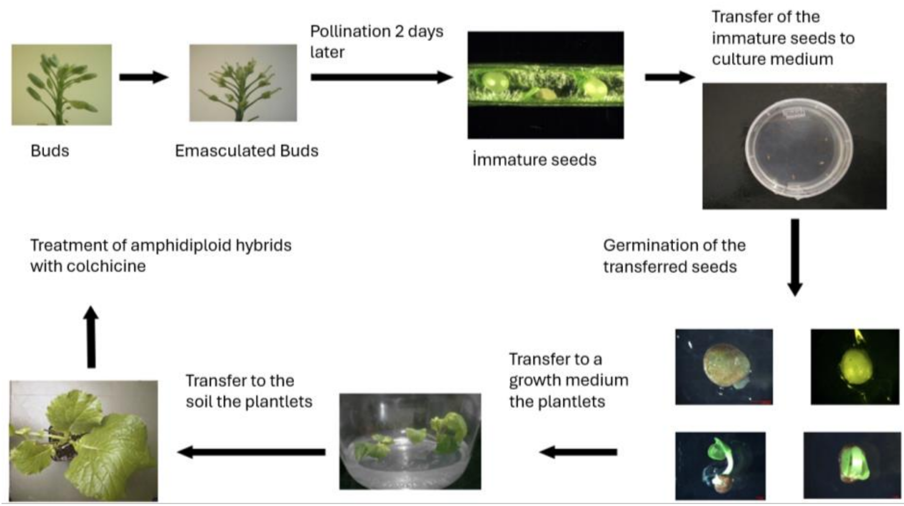

Figure 1. Obtaining rapeseed, an interspecific hybrid obtained by crossing cabbage and turnip, using the embryo rescue technique (Seyis et al., 2005).

Another important use of embryo culture in plant breeding is shortening the breeding period. In classical hybridization studies, it is necessary to wait for the embryo to mature within the seed. However, in the embryo culture technique, the embryo can be isolated and cultured when it reaches a stage where it can continue its physiological development. Thus, a new generation is obtained without having to wait for the seed to fully mature, and the generation period is significantly shortened (Figure 2). Especially when used together with speed breeding applications in annual plants, this technique contributes significantly to the completion of breeding programs in a shorter time.

The main advantages of embryo culture are summarized below:

i) It enables distant hybrids to be obtained by ensuring the preservation of embryo viability in crossbreeding between species and breeds.
ii) It provides fast and regular germination by eliminating seed dormancy.
iii) It significantly shortens the generation period in breeding programs.
iv) It makes it possible to obtain new plants without having to wait for seed maturation.
v) It allows the evaluation of seeds that have difficulty germinating or lose their viability in a short time.

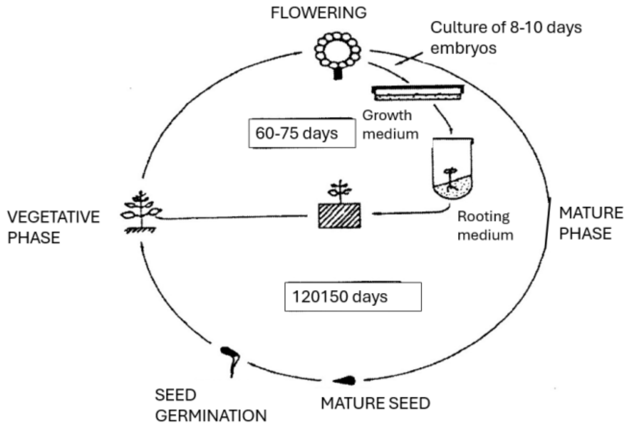

Figure 2. Shortening the life cycle of sunflower by culturing immature embryos (Bhojwani and Razdan, 1996).

vi) It constitutes an important experimental material in basic research on embryo development and seed physiology.

However, the method also has some limitations:

i) Isolation of embryos, especially in the early development period, requires a high level of technical skill.
ii) Depending on the development period of the embryo, the composition of the nutrient medium can vary significantly.
iii) Culture conditions need to be optimized according to species and genotypes.
iv) Contamination and embryo losses may occur during culture.
v) Even if embryo rescue is successful in some distant hybrids, sterility or chromosomal imbalances may occur in the resulting plants.

As a result, embryo culture is one of the most important cell and tissue culture techniques in plant breeding, especially in terms of embryo rescue and shortening the generation period. It is widely used in many plant breeding programs today due to its advantages in facilitating interspecies gene transfer, increasing hybridization success and accelerating the process of developing new varieties.

2.5. Obtaining a Haploid Plant

Haploid plants are plants that carry half the number of diploid (2n) chromosomes (n) in their normal somatic cells. These plants can be obtained by *in vitro* culturing of gametophytic tissues (such as microspore or egg cell) or as a result of some extensive hybridization systems. Since haploid plants carry a single set of chromosomes, artificially doubling the number of chromosomes results in completely homozygous double haploid (DH) plants.

Double haploid technology is considered one of the most important biotechnological applications in modern plant breeding. Because in classical breeding programs, consecutive breedings are required to develop homozygous lines and this process usually takes 5-8 years depending on the plant type. Moreover, although the theoretical homozygosity rate reaches very high levels through inbreeding, in practice it is very difficult to obtain a 100% homozygous individual at all loci. On the other hand, by doubling the chromosomes in haploid plants, completely homozygous double haploid lines can be obtained in a single generation. Thus, the breeding period is significantly shortened and selection processes can be carried out more reliably.

The main advantages of double haploid technology in plant breeding are:

- i) Homozygous lines can be obtained in a single generation.
- ii) The duration of breeding programs is significantly shortened.
- iii) As recessive genes appear directly in the phenotype, selection efficiency increases.
- iv) It provides high accuracy in genetic analyses, linkage maps and molecular marker studies.
- v) It accelerates the creation of parental lines in hybrid variety development programs.
- vi) It allows obtaining homozygous material in a short time in genetic transformation and mutation breeding studies.

Three main methods are used to obtain haploid plants under *in vitro* conditions:

1. Anther and microspore culture
2. Ovule and ovary (ovarium) culture
3. Embryo culture based on interspecies chromosome elimination (embryo rescue)

2.5.1. Anther and Microspore Culture

Anther culture is one of the most used methods in haploid plant production. In this method, anthers in the uninucleate development period of microspores are isolated under sterile conditions and placed in nutrient medium. Thanks to appropriate stress applications (such as heat shock, cold application or osmotic stress), the gametophytic development of microspores that would normally form pollen is stopped and they are directed to the sporophytic development path. Thus, embryo-like structures or calli are formed and haploid plants are regenerated from these (Sopory and Munshi, 1996; Çakır and Uysal, 2025).

In microspore culture, microspores are isolated from anthers and cultured directly in the medium. Although it is technically more difficult to perform than anther culture, it has many important advantages:

i) The development-suppressing effect of the anther wall is eliminated.
ii) Undesirable regeneration arising from diploid tissues such as the anther wall or connective tissue is prevented.
iii) While callus formation decreases, the rate of direct embryogenesis and regeneration increases.
iv) Since microspores come into direct contact with the nutrient medium, they can benefit from nutrients and growth regulators more effectively.
v) The rate of obtaining haploid plants increases.

Today, anther or microspore culture is routinely used in double haploid production in many cultivated plants, especially barley, wheat, rice, canola, pepper and tobacco.

2.5.2. Ovule and Ovary Culture

Another method used in haploid plant production is culturing the unfertilized egg cell or the ovule or ovary containing this cell. Since the unfertilized egg cell has a haploid (n) chromosome structure, haploid plants can be obtained by stimulating embryo development under appropriate culture conditions. This event is called gynogenesis. Natural development of embryos without fertilization is defined as parthenogenesis.

Gynogenesis is used as an alternative haploid production method, especially in species that do not respond well to anther culture. There are successful applications in onions, sugar beets and some types of vegetables.

2.5.3. Embryo rescue (embryo culture) in Hybrids Between Species and Genera

In some interspecies or intergeneric hybridizations, haploid plant production can be achieved together with the embryo rescue technique. In these systems, fertilization occurs normally, but in the early development stages of the embryo, chromosomes belonging to one of the parents are eliminated during cell divisions. The result is haploid embryos that carry only the single set of chromosomes belonging to the other parent. Since these embryos often cannot survive under natural conditions, they are isolated and cultured using the embryo rescue method.

This method is especially widely used in wheat × corn, *Hordeum vulgare* × *H. bulbosum* and similar chromosome elimination systems. The resulting haploid plants are initially sterile and cannot perform normal meiosis. Therefore, the number of chromosomes must be doubled.

The most used chemicals for chromosome folding are mitosis inhibitors such as colchicine and colcemid. These compounds prevent the separation of sister chromatids to the poles by inhibiting the formation of microtubules and spindle fibers during cell division. Since cytokinesis does not occur, the number of chromosomes doubles in the same cell, resulting in completely homozygous double haploid plants.

The individuals obtained here do not form a new species; Rather, they are pure lines of the current species that are homozygous at all gene loci. For this reason, double haploid technology is of great importance for the rapid creation of parental lines, especially in hybrid variety development programs (Figure 1).

As a result, haploid and double haploid technologies are one of the most effective biotechnological methods that can reduce the homozygosity process, one of the longest stages of classical breeding, to a single generation. Today, it is widely used in cereals, oil crops and many types of vegetables; It is considered one of the basic components of modern plant breeding, along with molecular breeding, genomic selection and gene editing technologies.

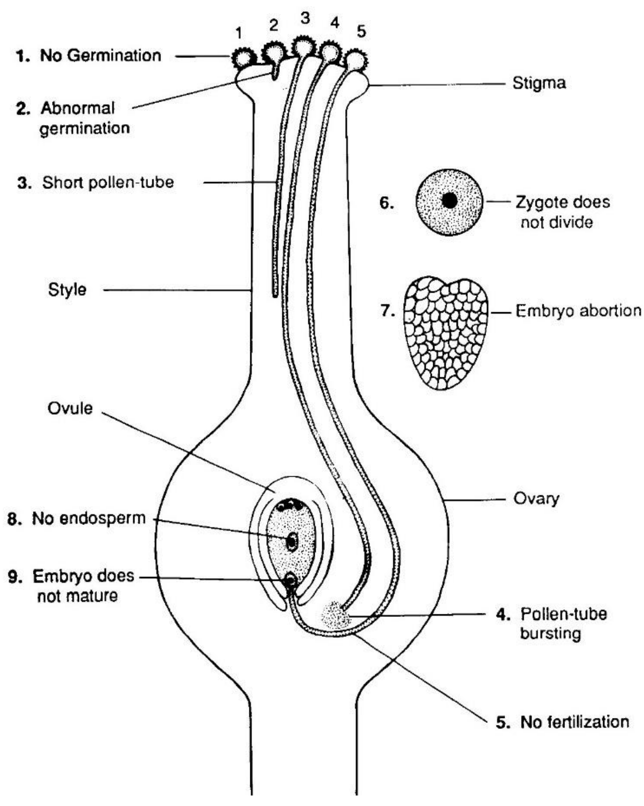

Figure 3. Incompatibility problems encountered in plants after pollination (Bajaj 1990)

2.6. *In Vitro* Pollination and Fertilization

One of the most important factors limiting the success of hybridization in plant breeding studies is the reproductive barriers that occur before and after fertilization. These obstacles are especially evident in crossbreeding between species and genera and make it difficult to obtain hybrid individuals using classical methods (Figure 3). *In vitro* pollination and fertilization techniques are important biotechnological methods developed to eliminate some of these obstacles under laboratory conditions.

Reproductive barriers encountered in hybridization studies are generally evaluated in two groups: pre-fertilization (prezygotic) and post-fertilization (postzygotic) barriers (Bajaj, 1990).

Obstacles before fertilization are mainly caused by the following reasons:

i) Inability of pollen grains to germinate on the pistil (stigma),
ii) Abnormal development of the pollen tube,
iii) The pollen tube cannot reach sufficient length in the pistil tube,
iv) The development of the pollen tube stops before reaching the ovary,
v) Fertilization cannot occur due to the pollen tube not being able to reach the embryo sac.

Obstacles after fertilization usually occur in the following ways:

i) Failure of the zygote to divide despite fertilization occurring,
ii) The development of the zygote stops after forming a few-cell embryo,
iii) Early degeneration of the embryo,
iv) Insufficient nutrition of the embryo due to the endosperm not developing normally,
v) The embryo loses its vitality before maturation.

Failure to achieve fertilization between pollen and female organ because of inbreeding is defined as self-incompatibility, and failure to fertilize in hybridizations between different species or genotypes is defined as cross incompatibility. These biological obstacles significantly limit the success of classical hybridization studies in many cultivated plants.

In vitro pollination and fertilization techniques are used as an effective method, especially in overcoming obstacles before fertilization. The basic principle of the method is that female reproductive organs are cultured under sterile conditions, and pollen is applied directly to the target tissue in a controlled laboratory environment. Thus, the physical and physiological obstacles that the pollen tube encounters in the natural environment can be largely eliminated.

In practice, different parts of the sterilized female organ can be used. These are stigma, stylus, ovary, placenta, ovule and embryo sac or directly egg cell.

It may happen. Sterilized pollen is applied to these tissues and pollen germination; pollen tube development and fertilization are encouraged under appropriate nutrient medium and culture conditions. In this respect, the method can be considered as the laboratory equivalent of controlled hybridizations carried out in the natural environment.

The main advantages of *in vitro* pollination and fertilization techniques in plant breeding are as follows:

i) It allows overcoming a significant part of the reproductive barriers before fertilization.
ii) It increases the success of hybridization between species and breeds.
iii) It contributes to fertilization in self-incompatible species.
iv) It allows pollen tube development to be examined under controlled conditions.
v) When used in conjunction with embryo culture and embryo recovery techniques, it increases the possibility of obtaining plants from distant hybrids.
vi) It constitutes an important experimental system in basic research on reproductive biology and fertilization physiology.

However, the method also has some limitations:

i) Application requires advanced sterile working techniques and experience.
ii) It is essential to optimize species-specific media and culture conditions.
iii) Even if pre-fertilization obstacles can be overcome, embryo or endosperm development disorders that occur after fertilization may continue. For this reason, it must be applied together with embryo culture (embryo rescue) in many studies.
iv) The success rate can vary significantly depending on the plant species and genotype.

As a result, *in vitro* pollination and fertilization is a biotechnological method that provides significant advantages, especially in hybridization combinations that cannot be achieved due to pre-fertilization obstacles under natural conditions. When used together with other cell and tissue culture techniques such as embryo rescue, protoplast fusion and genetic transformation, it makes significant contributions to the development of new genotypes that are difficult to obtain with classical methods.

2.7. Protoplast Culture and Somatic Cell Hybridization

A protoplast is a living cell surrounded only by a cell membrane, from which the cell wall has been removed by enzymes such as cellulase, hemicellulase, and pectinase, or by mechanical methods. The removal of the cell wall leaves behind a structure consisting of a cell membrane, cytoplasm, and nucleus. This structure has important applications, particularly in gene transfer and cell culture studies. In gene transfer studies, the cell wall constitutes a significant barrier limiting the entry of foreign genetic material into the cell. In protoplasts, this barrier is eliminated, making it easier for genes to enter the cell. Furthermore, protoplasts form the basic material for somatic cell hybridization studies.

In classical plant hybridization methods, the genomes of the parents are combined using the germ cells of the plants, and recombinant individuals carrying the genetic characteristics of both parents are obtained. However, the success of this method depends on the degree of kinship and genetic compatibility between the parents. Achieving successful results with classical hybridization, especially between plants of different genera or species that are not closely related, is quite difficult, and often impossible.

Somatic cell hybridization, on the other hand, is a biotechnological method that allows the creation of a new recombinant individual by combining the genomes of two different plants without using reproductive organs. In this method, protoplasts isolated from plants are combined in suitable culture media with the help of chemical or physical applications that promote fusion. If both the nuclei and cytoplasms fuse because of fusion, a somatic hybrid is formed, while if the nucleus and cytoplasm of one cell fuse with only the cytoplasm of the other cell, a somatic cybrid is formed (Hatipoğlu, 2012). Somatic cell hybridization is an important biotechnological approach that allows the creation of genetic combinations, especially between closely or distantly related species, that cannot be hybridized using classical plant breeding methods.

2.8. Conservation of Genetic Material

Today, the rapid increase in the world's population, industrialization, urbanization, destruction of natural habitats, and changes in agricultural production systems are putting pressure on many plant genetic resources, causing genetic erosion. As a result, some genetic resources are completely lost or becoming increasingly difficult to access. Understanding the importance of this situation, many countries, especially developed ones, have developed various strategies for the conservation of plant genetic resources.

Two main conservation approaches are applied in the conservation of plant genetic resources: in situ and ex situ. In situ conservation focuses on preserving genetic material in its natural habitat, while ex situ conservation relies on preserving genetic material outside its natural growing environment. One of the most common ex situ conservation methods is *in vitro* conservation techniques.

For species that can be propagated by seed and whose seeds can maintain their viability for a long time, seed preservation is the most economical and effective ex situ conservation method. However, this method cannot be applied to species that do not produce seeds, whose seeds have a short lifespan, or whose genetic structure cannot be preserved by seed due to high heterozygosity. In such cases, plants are preserved vegetatively *in vitro*. *In vitro* preservation encompasses not only whole plants but also various plant materials such as meristems, shoot tips, stems, leaves, cells, calluses, pollen, and even DNA, all of which can be stored for extended periods.

The primary goal of *in vitro* preservation is to maintain the viability of plant material for a long time by slowing down its metabolic activity and growth. This is achieved through methods such as coating the plant material with mineral oil, storing it at low temperatures, growing it in carbon-free or low-nutrient media, or adding growth-retarding chemicals like abscisic acid (ABA), mannitol, or dimethylsuccinic acid to the nutrient medium. Furthermore, cryopreservation (freezing), which involves treating plant cells with cryoprotectants such as sugars, glycerol, or dimethyl sulfoxide (DMSO) and storing them for extended periods in liquid nitrogen (-196 °C), is also widely used for the long-term preservation of genetic resources.

The main advantages of *in vitro* preservation are:

i) It allows for the safe preservation of numerous clonal, sterile, or vegetatively propagating plant species for extended periods.
ii) Only a small amount of plant material is required for preservation.
iii) It offers quick and easy access to the stored material when needed.
iv) There is fewer quarantine issues encountered in the international exchange of materials such as pollen compared to seeds or other propagation materials.

The main disadvantages of *in vitro* preservation are:

i) There is a risk of somaclonal variation occurring under long-term culture conditions.
ii) Appropriate preservation protocols must be developed separately for each plant species.
iii) It is more expensive than other preservation methods due to the need for laboratory infrastructure, technical knowledge, and continuous maintenance.

2.9. Gene Transfers

The main goal in classical plant breeding methods is to combine the superior characteristics of two or more plants into a single genotype. However, in these methods, the transfer of unwanted genes along with desired characteristics to newly created recombinant individuals constitute a significant disadvantage. In addition, classical hybridization methods can only be applied between sexually compatible species, and gene transfer does not provide targeted transfer due to the co-transfer of large chromosome segments.

Gene transfer technologies, on the other hand, allow the direct transfer of the desired gene into plant cells, making it possible to develop transgenic plants that acquire only the target characteristics. In this method, the gene to be transferred is first isolated and cloned into a suitable vector DNA. Then, the recombinant DNA is transferred to bacteria, usually Escherichia coli, for amplification. In gene transfer to plant cells, the biological transformation method is mostly used via Agrobacterium tumefaciens; In addition, particle bombardment (biologic method), microinjection, electroporation, and various chemical transformation methods are also utilized (Özcan et al., 2004; Hatipoğlu, 2012; Kurt, 2023).

One of the most important advantages of gene transfer technologies is that gene transfer occurs only at the gene level, and therefore, undesirable genetic characteristics are not carried together. Furthermore, thanks to this technique, genetic material can be transferred not only between closely related plants but also between different plant species, and even between plants and bacteria, fungi, or other groups of living organisms. Thus, the limitations of interspecies hybridization in classical plant breeding have been largely eliminated, and new opportunities for increasing plant genetic diversity have been provided.

Thanks to gene transfer technologies, the nutritional value of plants can be increased, resistance to diseases and pests can be gained, tolerance to abiotic stress factors such as herbicides, drought, salinity, and low temperatures can be developed, the taste, aroma, shelf life, and quality characteristics of products can be improved, and the metabolic activities of plants can be regulated to increase yield and production performance. Therefore, gene transfer is considered one of the most important application areas of modern plant biotechnology and molecular plant breeding.

3. Potential Use of Cell and Tissue Culture Techniques in Plant Breeding

Cell and tissue culture techniques are among the important biotechnological tools in plant breeding for increasing genetic variation, developing superior genotypes, and efficiently utilizing genetic resources. While gene transfer in classical plant breeding methods is largely limited to sexually compatible and closely related species, modern biotechnological applications supported by tissue culture techniques enable gene transfer between distantly related species, and even different groups of organisms. This significantly expands the genetic diversity that can be used in plant breeding.

Tissue culture techniques also allow for the rapid and reliable multiplication of valuable genetic materials that are difficult or impossible to multiply with classical methods, while preserving their genetic stability. Thus, it becomes possible to preserve superior genotypes and ensure a continuous supply of healthy plant material for use in breeding programs. These techniques offer a significant advantage, especially in vegetatively propagating species, in obtaining disease-free plant material and multiplying it in large numbers in a short time.

Cell and tissue culture applications also offer significant advantages to plant breeders by enabling *in vitro* selection studies. Under controlled laboratory conditions, numerous genotypes can be screened in a short time against various biotic and abiotic stress factors such as disease agents, salinity, drought, heavy metal toxicity, or herbicide tolerance, and individuals exhibiting superior characteristics can be selected. Thus, a faster and more effective selection process can be carried out regardless of climate and environmental conditions.

In addition, cell and tissue culture techniques play an important role in the conservation of plant genetic resources. Thanks to *in vitro* preservation and cryopreservation methods, valuable genetic materials can maintain their viability and genetic characteristics for a long time, thus ensuring the transfer of existing genetic resources to future generations. This is of great importance both for the conservation of biological diversity and for providing resources for future plant breeding studies.

In conclusion, cell and tissue culture techniques; With numerous application areas such as rapid propagation, disease-free plant production, haploid plant generation, embryo rescue, somatic embryogenesis, protoplast fusion, gene transfer, *in vitro* selection, and genetic resource conservation, cell and tissue culture techniques have become an indispensable component of modern plant breeding. Along with advancements in molecular biology and genome editing technologies, it is predicted that cell and tissue culture techniques will continue to be among the fundamental biotechnological methods that enhance the effectiveness of plant breeding and contribute to sustainable agricultural production in the future.

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Chapter 4

Mass Plywood Panels (Mpp): A Paradigm Shift in Timber Construction Technology

Mutlu TÜRK[1], İlker YALÇIN[2], Vedat ÇAVUŞ[3]

1. Engineered Wood Products (EWP)

Due to restrictions on forest resources, increasing environmental pressures, and the shrinking of forest areas, the supply of solid wood material is becoming increasingly difficult; this situation is leading to price increases and difficulties in securing lumber of structural dimensions. These challenges have made it necessary to utilize smaller-diameter, fast-growing tree species with limited economic value in the production of engineered wood products (EWP) (Mengeloğlu and Kurt, 2004; Çavuş 2019A, Çavuş 2019B).

EWP (Engineered Wood Products) are composite materials produced by bonding wood-based components—such as lumber, veneer, particleboard, strand board, and fiberboard—and pressing them under heat and pressure (Heräjärvi ve ark., 2004). These products are classified into four main groups: structural composite lumber, structural wood panels, laminated wood products, and wooden I-beams (Kurt et al., 2003). MAM production increases the utilization rate of logs; compared to solid lumber, it offers higher dimensional stability, greater strength, and lower physical and mechanical variation. (Carrick and Mathieu, 2005; Kurt et al., 2008).

EWP's were first manufactured in the United States; the process began with laminated veneer lumber and continued with parallel-strip lumber and laminated-strip lumber (Winistorfer and Steudel, 2000). From these materials used in the aircraft industry in the 1960s, two types were developed: "compreg," produced by applying pressure to the laminates, and "impreg," produced without applying pressure (Nelson, 1997). While "impreg" refers to the process of increasing density by filling the voids in wood cells with synthetic resins, "compreg" is a

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resin-impregnated and compressed wood material (Kamke, 2006; Kultikova, 1999).

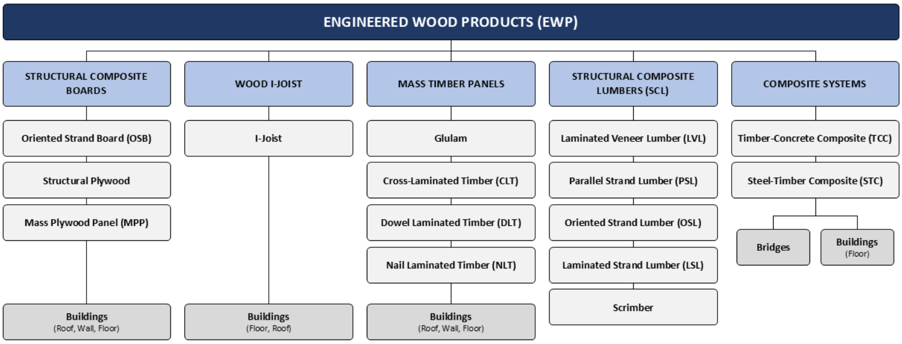

Figure 1. Engineered Wood Products (Winistorfer and Steudel, 2000).

Figure 1 presents a comprehensive classification of EWP products. According to this classification, Mass plywood panels (MPP), which fall within the structural wood panels group, are an engineered wood product that stands out particularly for its multilayer structure and high structural performance. The production technology, physical and mechanical properties of MPP, as well as a comparison with traditional plywood and other solid wood panels, will be discussed in the remainder of this section.

2. Mass Plywood Panels – MPP

Mass Plywood Panels (MPP) are a relatively new engineered wood product manufactured by Freres Engineered Wood, created by cross-laminating structural-grade veneers. Each 25.4 mm-thick layer consists of seven veneers oriented lengthwise and two veneers oriented crosswise (Field et al., 2023). Unlike cross-laminated timber (CLT), MPP is produced by orienting structural-grade plywood veneers in specific ratios (e.g., 80% lengthwise, 20% crosswise) instead of using solid wood (Ho et al., 2022; Kiss et al., 2025). Unlike laminated veneer lumber (LVL), MPP orients its veneers not entirely in the same direction but in specific cross-directional ratios. As a result, MPP achieves bidirectional load-bearing capacity and superior dimensional stability compared to LVL's unidirectional strength. The most distinctive feature distinguishing MPP from traditional plywood is panel thickness. While there is no universal terminological definition regarding the thickness limits of solid wood panels, a thickness range of 45 mm to 500 mm is generally accepted for CLT panels used in structural walls and floors. The literature suggests that for a product to be classified as "mass timber" in structural applications, it must meet a minimum thickness threshold of 45 mm. This threshold is also supported by the maximum production limits for lightweight panels (Gagnon and Pirvu, 2012; De Araujo et al., 2025).

The purpose of this section is to detail the production stages of MPP, compare its performance with other engineered wood products (LVL, CLT, PSL), and describe its innovative applications in earthquake engineering.

(A) (B)

Figure 2. MPP panel views (url1, url2)

Solid plywood panels (MPP), whose general appearance is shown in Figures 2A and 2B, are commonly known as Mass Plywood Panels. The MPP building system is an innovative construction approach in which engineered wood products are used as primary structural members (Kremer and Symmons, 2015). As one of the newest and most notable members of this system, solid plywood panels offer a sustainable alternative to traditional steel and concrete structures, particularly in multi-story wood buildings (Kiss et al., 2025). MP P differs from other solid wood products (particularly lumber-based cross-laminated timber—CLT) in that it uses structural-grade plywood veneers as the building blocks instead of solid lumber (Kiss et al., 2025). First developed by Oregon (U.S.)-based Freres Lumber Co., Inc., this product is defined as a "heavy-duty green engineering product" that delivers predictable structural performance in industrial walls, floors, and frames (De Araujo et al., 2025).

There are only two active MPP producers in the world: Freres Engineered Wood in the United States and Metsä Wood in Finland. Freres's facility in Lyons, Oregon, has an annual production capacity of 35,000 cubic meters, while Metsä's facilities in Lohja and Punkaharju have a combined annual production capacity of 270,000 m^3. Metsä will increase this capacity to 430,000 m^3 with a new facility in Äanekoski, representing an investment of 300 million euros, which is scheduled to come online in 2026. Both manufacturers hold environmental certifications (FSC, PEFC, ATFS, ISO 14025) and engage in sustainable production.

A typical MPP panel has a layer arrangement optimized for its intended end use. The panel structure generally consists of two main components (Miyamoto et al., 2020; Freres, 2022). The first of these are the face panels. These panels are the layers located on both outer surfaces of the panel. In these layers, approximately 80% of the veneers are oriented along the strong axis (longitudinal), thereby maximizing the panel's axial stiffness (Soti et al., 2020). The second component consists of core panels. These are the inner layers, the number of which is determined based on the desired total thickness. In these layers, the veneers are oriented equally in both directions (cross-banding), thereby ensuring the dimensional stability of the MPP. In a study made by Minamoto et al. (2020) was defined the MPP configuration as total panel thickness 76.2 mm, and three main layers each tickness 25,4 mm and at each layer using nine Douglas fir (Pseudotsuga menziesii) veneers.

The most distinct difference between MPP and traditional plywood is panel thickness. While traditional plywood is typically manufactured to a maximum thickness of 30–40 mm, MPP panels have a wide range of thicknesses, varying from 51.8 mm to 310.8 mm (De Araujo et al., 2025). In the literature, the minimum thickness limit for solid wood products is generally accepted as 45 mm (Gagnon and Pirvu, 2012). MPP's production range, which starts at 51.8 mm, technically classifies this product as "solid wood." Thanks tothis characteristic MPP to transcend its status as a thin sheet material and enables its use in buildings as both vertical (wall) and horizontal (floor) load-bearing elements.

In recent years, changed the scale of usage of this raw material due to a shift towards solid wood systems with high carbon sequestration capacity at combating global warming extent. Oriented strand boards (OSB), traditionally produced from strand chips, and standard plywood made from veneers are increasingly being replaced by thicker and wider panels. In this context, MPP has ushered in a new era in the industry by bringing the high strength provided by veneer technology to the scale of solid panels. MPP makes a significant difference in terms of raw material efficiency, particularly when compared to wood-based products such as cross-laminated timber (CLT). The use of veneers obtained from small-diameter logs enables more efficient utilization of forest resources. Furthermore, the fact that 80% of the veneer layers are oriented longitudinally gives MPP superior dimensional stability and a homogeneous strength structure. In addition, the high energy dissipation capacity required in seismic zones makes

MPP indispensable as a flooring and wall element, particularly in multi-story wood buildings.

2.1. Mass Plywood Panel Production

Mass plywood panels (MPP), whose production process is schematically shown in Figure 3, are typically manufactured in ten basic steps, although there may be slight variations from one manufacturer to another. These steps are: (1) raw material procurement, (2) preparing logs for veneer production (softening and debarking), (3) veneer production (peeling), (4) drying the veneers, (5) grading the veneers, (6) gluing the veneers, (7) orienting the layers to form a blank, (8) pressing, (9) sizing and sanding, (10) packaging and shipping (De Araujo et al., 2025; Freres, 2022).

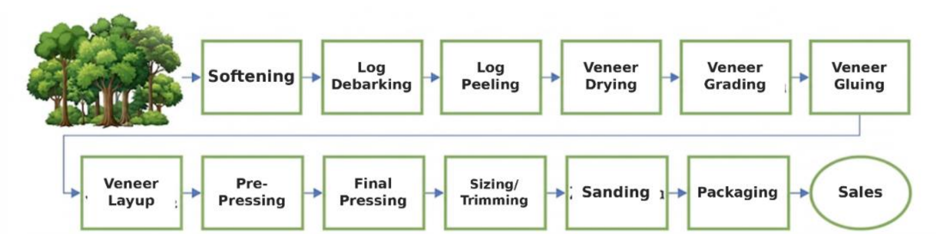

Figure 3. MPP Production Process Diagram

Thanks to this production technique, characteristics inherent in the natural structure of wood—such as knots, cracks, and fiber twists—that reduce strength are distributed throughout the product, thereby eliminating or minimizing them. This applies to laminated veneer lumber (LVL), laminated strip lumber (TŞK/LSL), parallel strip lumber (PŞK/PSL), and cross-laminated timber (ÇTK/CLT), limits the dimensional change of MPP, thereby providing predictable strength properties and dimensional stability. MPP is a patented product, and its specific engineering properties and dimensions are unique to each manufacturer. Therefore, there is no common production standard or design values for MPP. Design values are derived from test results analyzed in accordance with CSA O86 and ASTM D5456 (De Araujo et al., 2025).

The first stage of MPP production consists of the processes of preparing logs for veneer production, procuring them, transporting them, soaking them, and peeling their bark. Freshly cut logs are retrieved from storage and placed in a hot water tank. Soaking the logs softens the wood, making it easier to remove the bark and separate the veneers, while also preventing splinter formation. To increase efficiency, the temperature of the hot water tank is raised under cold weather conditions (Freres, 2022). MPP can be manufactured from fast-growing species as well as from trees with wide and relatively small diameters. There are no restrictions on raw materials for MPP production. Freres Lumber uses veneers derived from second- and third-generation forest products with a minimum diameter of 5 inches (127 mm) (De Araujo et al., 2025). Many waste materials generated during production at wood-processing plants, particularly small pieces, can be utilized as a raw material source for MPP production.

The process of debarking the logs is followed by the process of producing veneers. Peeling machines are used in the production of MPP veneers (De Araujo et al., 2025). Softening (conditioning) of logs is a critical pretreatment for veneer quality. This process is typically carried out in hot water baths, hot water spray chambers, or steam chambers (Chen et al., 2021). The target temperature depends on the tree species; higher temperatures are required for knotty species, hardwoods, and frozen logs. High temperatures reduce deep surface cracks (lathe checks) during peeling, improve veneer integrity, lower energy consumption, and protect the blade. However, excessive heating can lead to surface fuzziness, color distortion, and hydro-degradation (Chen et al., 2021). Therefore, it is necessary to determine the optimal conditioning temperature that balances veneer quality and production costs.

The resulting coatings are conveyed to drying ovens via conveyor belts. Cylindrical drying ovens are commonly used to dry the coatings employed in MPP production. The coatings are dried until their moisture content reaches 8% (±3) (Freres, 2022). Since moisture content has a significant effect on the mechanical and physical properties of the resulting MPP, the drying of the coatings is of critical importance. Various optimization ranges have also been reported in the literature; for example, one study indicated that the best adhesion results were achieved when the coating moisture content was in the 4–6% range (Aydın et al., 2006).

After the drying process, the coatings are sorted and the coating process begins. The amount of adhesive applied varies depending on the manufacturer and the intended use of the final product, but generally ranges from 4% to 8% of the coating's weight. To ensure even distribution of the adhesive, the gluing process is carried out using a roller gluing machine or a spray method.

Adhesives can be classified not only by their structural, semi-structural, and non-structural applications but also by their permanence and durability. Adhesives must be compatible with the bonding conditions under which they are commercially used. Heat-curing adhesives allow for slow curing at room temperature (giving time for wood components coated with the adhesive to be brought together for assembly), allow adjacent wood surfaces to come into close contact with the aid of heat and moisture, and cure rapidly when heated while minimizing rebound when pressure is released; as a result, they are compatible with the manufacture of engineered wood products (Frihart, 2005). Forest industry products generally rely on the bonding process.

The production process for these products is largely based on the gluing and bonding of wood veneers, strips, fibers, chips, and small pieces. This has made the widespread use of synthetic adhesives in the forest industry a necessity. Today, adhesives are used in 80% or more of the products manufactured in the forest industry, and approximately 70% of the total volume of adhesives produced worldwide is consumed by the forest industry (Wålinder, 2000). When classified according to their structural properties, structural adhesives suitable for outdoor use include phenol-formaldehyde, resorcinol-formaldehyde, phenol-resorcinol-formaldehyde, isocyanate, melamine-formaldehyde, and melamine-urea-phenol-formaldehyde (Vick, 1999). In this context, the primary adhesive type used in MPP production is melamine-formaldehyde (MF) resin. While phenol-formaldehyde (PF) is widely used in other structural composite lumber (SCL) products, MF is the preferred adhesive for MPP (Puettmann and Sinha, 2020; Freres, 2022; Metsä, 2023). Although the adhesive application rate varies depending on the manufacturer and the intended use of the final product, it is generally between 4% and 8% of the panel weight. The adhesive is applied using a roller or spray method to ensure even distribution, and the panels are continuously measured and fed into the mixer until the desired adhesive amount is reached (Freres, 2022).

In MPP production, orienting all layers in the same direction or at a specific cross-grain ratio is one of the most critical stages of the process. In Freres' F16-class panels, seven of the nine veneers are oriented longitudinally, whereas in the F10 class, the veneers are oriented perpendicular to adjacent layers (De Araujo et al., 2025; Freres, 2022). In the production of laminated veneer lumber (LVL), all veneers are oriented in the same direction, whereas in the production of cross-laminated timber (CLT), the layers are arranged perpendicular to one another. MPP, on the other hand, offers a combination of these two approaches. Mechanical methods (orienting belts, stacking robots) are used to orient the veneers.

MPP composites are certified in two different structural classes, designated F16 and F10 (Figure 4). These classes are distinguished primarily by differences in performance along the major and minor force directions and must be carefully evaluated during the design phase. Both classes utilize density-graded laminates, and the production of the approximately 25.4 mm-thick laminate layers is guided by specific combinations (Freres Engineered Wood, 2023).

F16-class MPPs consist of nine veneer layers, seven of which are oriented longitudinally (lengthwise) and two of which are oriented crosswise (widthwise). The F16 class should be preferred in situations where clearances in the principal force direction are of primary importance.

The F10 class, on the other hand, has a structure similar to that of traditional plywood, in which each veneer layer is oriented at a 90-degree angle to the adjacent layer. Although the load-bearing capacity in the primary direction is lower in this class compared to F16, it performs better in the secondary direction. Therefore, the F10 class is suitable for applications where bidirectional load-bearing capacity is preferred (Freres Engineered Wood, 2023).

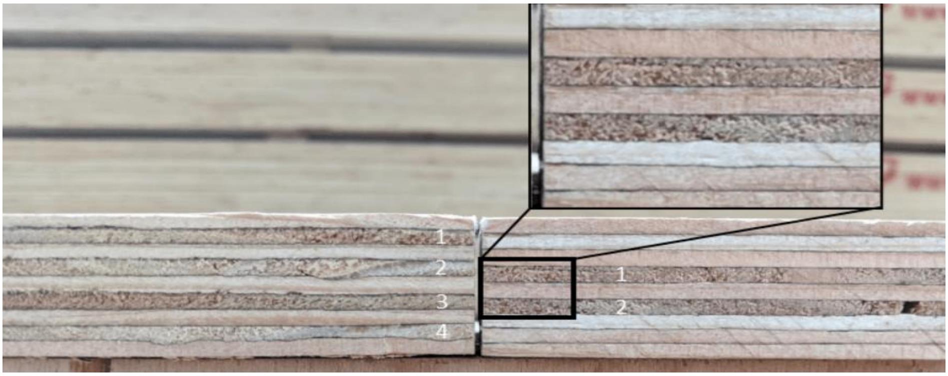

Figure 4. Comparison of the F16 and F10 layer arrangements in the MPP (Freres Engineered Wood, 2023).

The lamination process is followed by the pressing process. MPP panels are manufactured using water-resistant phenol-formaldehyde (PF) resin. Pressing is carried out at 120–130°C; however, if the temperature exceeds 130–135°C, cohesion decreases and defects occur. High temperatures, particularly when the veneer has high moisture content, can cause defects such as excessive adhesive penetration and insufficient bonding; they can also trigger bubble formation along the adhesive line. Thanks to modified PF resins, the pressing temperature can be reduced to 100–110°C; however, cold pressing is not preferred because it is inefficient. The pressing time varies between 10 and 30 minutes, depending on the panel thickness. If curing is insufficient, strength decreases; if it is excessive, the adhesive becomes brittle (Sedliacik et al., 2010; Qin and Teng, 2022; De Araujo et al., 2025). In high-resin wood species, extractives accumulating on the surface can reduce the adhesive's wetting and penetration ability (Vick, 1999).

In MPP production, if the blank is to be fed into a discontinuous press, it is dimensioned; in a continuous system, however, the blank is pressed continuously and dimensioned after exiting the press. In addition, smaller panel pieces are joined using the scarf joint (Figure 5) technique (beveled edge joint) with six-axis robots to form large-sized panels (De Araujo et al., 2025). Scarf (beveled edge) joining is a joining technique based on cutting the ends of two material pieces at a specific angle and bonding or mechanically fastening these beveled surfaces together. This method provides high bond strength without causing an increase in thickness at the joint. The beveled surface increases the bonding area, which in turn provides high structural integrity and strength. This technique, which is more durable than straight-edge joints, is particularly preferred in the production of large-sized solid wood panels (Arciszewska-Kędzior et al., 2015). The pressing temperature varies depending on the type of adhesive used. The pressing time, on the other hand, varies depending on the thickness of the MPP being produced and is typically applied for 10 to 30 minutes.

Figure 5. Edges shaped using the "Scarf" (beveled edge) joining technique (Freres Engineered Wood, 2023).

After the pressing and sizing processes, the panels are sanded, undergo quality control, and are packaged. During storage, MPP panels must be packaged in a way that prevents changes in moisture content due to the hygroscopic nature of the wood material.

2.2. Applications of Mass Plywood Panels

The specific engineering properties and dimensions of MPP vary by manufacturer. Therefore, while there is no common production standard or design values for MPP, the design values are derived from test results analyzed according to CSA O86 and ASTM D5456 (De Araujo et al., 2025). One of the key differences between structural composite lumber and solid wood products is their intended applications. Parallel strand lumber (PSL) is used in building construction as beams, columns, and headers. It is also preferred in wood bridge construction for bridge deck, bridge railing, bridge beams, and columns (Trus Joist, 2005). Laminated strip lumber (LSL) can be used as a load-bearing element in residential and commercial buildings. Laminated veneer lumber (LVL), on the other hand, is used in structural applications such as beams, headers, and rafters (Kurt et al., 2012).

Mass plywood panels (MPP) are a structural product used as flooring, wall, and roof panels in wood-frame construction. It can also be used as beams and columns (Freres, 2022; Metsä, 2023). While MPP shares similar application areas with cross-laminated timber (CLT), its veneer-based production process provides more homogeneous mechanical properties. Pioneering projects utilizing MPP include the 19- and 5-story "oWOW" high-rise buildings in the U.S., "Peavy Hall" and the "Advanced Wood Products Laboratory" at Oregon State University, the Freres Engineered Wood Timber Department warehouse in Oregon, the Redmond Senior and Community Center in Washington, the "Coronation" sports and recreation center in Canada, and the "Monad Granville" mixed-use high-rise residential building in Vancouver, scheduled for completion in 2026 (De Araujo et al., 2025; Freres, 2024; Metsä, 2024). Mjøstårnet (85.4 m, 18 stories, Norway), although it does not use MPP, features a hybrid structural system consisting of laminated timber (Glulam) columns and beams, laminated veneer lumber (LVL) panels, CLT, and concrete-wood composite floors (Liven and Abrahamsen, 2023). Such projects are significant in demonstrating how solid wood structures can be diversified using various engineered wood products (GLT, LVL, CLT, MPP).

2.3. Advantages and Disadvantages of Mass Plywood Panels

According to studies by De Araujo et al. (2025), Kiss et al. (2025), and Miyamoto et al. (2020), MPP offers numerous potential advantages. First and foremost is raw material flexibility: There are no limitations on the raw materials used for production, as MPP can be manufactured from fast-growing species as well as relatively small-diameter trees and even industrial waste (De Araujo et al., 2025). Material efficiency is another advantage. MPP can provide the same structural performance as cross-laminated timber (CLT) while using 20–30% less wood raw material (Dalheim, 2016; De Araujo et al., 2025). The production process is highly automated, resulting in very high efficiency.

In terms of connection performance, the performance of MPP can also be enhanced using mechanical fasteners. Tests have shown that MPP connections exhibit higher capacity compared to similar CLT connections. For example, in screw-bracketed MPP connections, the shear capacity was measured at 23 kN and the tensile capacity at 25 kN, whereas in CLT, these values were measured at 14.6

kN and 13.1 kN, respectively (Miyamoto et al., 2020). Predictable strength properties are also a significant advantage of MPP. Compared to sawn lumber, MPP has higher strength properties and is denser. Furthermore, thanks to the controlled production of the veneers and the distribution of natural defects, its strength properties are more homogeneous and predictable.

In terms of fire resistance, MPP provides self-insulation through the charring of its outer layer in the event of a fire, which is a general characteristic of solid wood products. The charring rate is reported to be 0.66 mm/min for Freres panels and 0.7 mm/min for Metsä panels (De Araujo et al., 2025; Freres, 2022; Metsä, 2023). Sustainability is another advantage: Produced from a renewable source, due to its carbon sequestration properties MPP has a lower carbon footprint compared to steel and concrete. Both manufacturers hold environmental certifications (FSC, PEFC, ATFS, ISO 14025) (De Araujo et al., 2025). Lightweight construction is also among the advantages. MPP weighs approximately one-sixth as much as a reinforced concrete slab of the same dimensions; This situation facilitates transport and assembly while simultaneously reducing seismic loads. Finally, the potential for self-centering is a notable advantage of MPP. When MPP walls are equipped with post-tension tendons, self-centering systems capable of returning to their original position after an earthquake can be created (Soti et al., 2020).

In addition to its advantages, MPP also has certain limitations (Nelson, 1997; De Araujo et al., 2025; Miyamoto et al., 2020; Soti et al., 2020). The first of these is its low tensile strength. Due to its plywood-based structure, MPP's tensile strength is 15–30% lower than that of solid wood; this requires more careful design, particularly at connection points (Miyamoto et al., 2020). Another disadvantage is the excessive use of adhesive. MPP uses more adhesive than CLT, which can make MPP less attractive than CLT in terms of its life-cycle footprint (Bolduc, 2020; De Araujo et al., 2025). High capital investment is also a significant disadvantage: Due to the complex production process, an MPP production line requires a substantial capital investment; the cost of Freres's Lyons facility has been reported to be approximately 40 million U.S. dollars (De Araujo et al., 2025).

A limited network of producers is another disadvantage of MPP. The MPP industry has not yet reached a global scale, with only two active producers worldwide (Freres and Metsä). This situation is a limiting factor in terms of supply chain security and competition (De Araujo et al., 2025). Dimensional stability is also among the disadvantages. The dimensional stability of MPP—particularly its tendency to swell in the thickness direction—is not as good as that of solid wood in some cases; therefore, additional precautions may be necessary when using it in humid environments. Density is another disadvantage: MPP can be heavier than solid wood of the same dimensions. For example, while the density of Freres MPP is 500 kg/m³, the density of solid wood of the same type ranges from approximately 450 to 480 kg/m³ (De Araujo et al., 2025). Finally, the risk of permanent displacement in seismic performance presents a disadvantage. Depending on the type of complementary energy dissipation systems, permanent displacement (residual drift) may occur in hybrid MPP walls following an earthquake (Soti et al., 2020).

The practical application of MPP systems in detached house construction presents technical difficulties that differ from those of traditional wood-frame systems. Case studies have shown that due to the substantial weight of the solid panels (approximately 227 kg/panel), the use of cranes is mandatory during the installation phase, and this impacts site logistics (Onan, 2024). Furthermore, the solid structure of MPP requires more detailed advance planning for the routing of mechanical, electrical, and plumbing (MEP) pipes; it is emphasized that random drilling or cutting on-site poses structural risks and presents implementation challenges (Onan, 2024).

3. Results and Discussions

Mass plywood panels (MPP) represent a significant innovation in solid wood technology. Thanks to a veneer-based production approach, they offer higher material efficiency (20–30 percent less wood raw material) and more homogeneous mechanical properties compared to cross-laminated timber (CLT). Studies on the connection performance of MPP have shown that the European Yield Model can be used to calculate the yield loads of MPP connections and that MPP connections exhibit higher capacity compared to similar CLT connections. Studies on the seismic performance of MPP have yielded promising results, particularly in the context of self-centering shear walls. In an experimental study by Soti et al. (2020), it was demonstrated that MPP walls, when equipped with shear friction connections added to a post-tension system, can achieve both high energy dissipation capacity and the ability to self-center after an earthquake. However, it was also found that high energy dissipation capacity could result in greater permanent displacement. Therefore, an optimal balance between energy dissipation and permanent displacement must be established in the design of MPP-based seismic resistance systems.

Since MPP is a new commercial wood-composite product, research on this product is quite limited. It is believed that supporting efforts and research aimed at the promotion, production, and development of this product would be beneficial. The following topics are suggested for future research:

The long-term creep behavior of Plywood should be investigated. Plywood performance should be evaluated under different climatic conditions. A new generation of lower-emission (bio-based and formaldehyde-free) adhesives should be developed. The suitability of fast-growing tree species in Turkey (poplar, eucalyptus, and red oak) for plywood production should be investigated. Hybrid systems (MPP-steel, MPP-concrete, and various energy-damping combinations) aimed at improving the seismic performance of MPP should be developed and optimized. In MPP-based self-centering walls, the relationship between energy-damping capacity and permanent displacement should be modeled in greater detail, and design parameters should be determined. Coating materials and fire retardants aimed at improving the fire resistance of MPP should be investigated. The environmental impact should be reduced by optimizing the amount of adhesive used in MPP production. Additionally, the technological adaptations required for traditional plywood manufacturers to transition to MPP production should be identified.

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Chapter 5

Fish Migration for Reproduction: Biological Strategies and Conservation

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Abstract

Fish migration for reproduction is a fundamental ecological process that enables many fish species to complete their life cycles by moving between feeding, growing, and spawning habitats. This chapter reviews the biological significance, mechanisms, and conservation of reproductive migration in freshwater, estuarine, and marine fishes. It explains how reproductive migration enhances spawning success, egg and larval survival, life-cycle completion, and genetic diversity through habitat connectivity. The major reproductive migration patterns—anadromous, catadromous, potamodromous, oceanodromous, and amphidromous—are described, together with representative examples including salmon, European eel, sturgeon, and tuna. The chapter also examines the environmental and physiological factors regulating migration, highlighting the roles of temperature, water flow, salinity, photoperiod, chemical and geomagnetic cues, as well as osmoregulation, endocrine control, energy storage, muscle endurance, and reproductive transformations.

Major anthropogenic threats, including dams, habitat fragmentation, climate change, pollution, habitat degradation, and overfishing, are discussed as critical factors disrupting migration routes and reducing reproductive success. Conservation strategies such as fish passages, river restoration, protection of spawning grounds, seasonal fishing restrictions, hatchery management, and international cooperation are evaluated as essential tools for maintaining migratory pathways and sustaining fish populations.

The chapter emphasizes that successful conservation should focus on protecting the entire reproductive pathway rather than isolated habitats, integrating habitat connectivity, ecosystem restoration, and long-term monitoring. Maintaining reproductive migration is vital for preserving biodiversity, supporting sustainable fisheries, and ensuring the resilience of aquatic ecosystems under increasing environmental pressures.

Keywords: Fish migration, Reproductive migration, Spawning grounds, Anadromous migration, Catadromous migration, Habitat connectivity

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1. INTRODUCTION

Fish migration is a major biological process through which fish move between habitats to complete important stages of their life cycle. Among the different purposes of migration, reproduction is one of the most significant because many fish species must reach specific spawning grounds where environmental conditions are suitable for egg development, larval survival, and recruitment into the population. These movements may occur within freshwater systems, within marine environments, or between freshwater and seawater, depending on the life-history strategy of the species (Harden Jones, 1968; Lucas and Baras, 2001; McDowall, 1988).

Reproductive migration is especially important in species that depend on particular spawning habitats. For example, salmon migrate from the ocean to freshwater rivers to spawn, while eels migrate from freshwater or coastal habitats to oceanic spawning areas. Such migrations are not random movements; they are usually seasonal, directional, and controlled by environmental cues such as water temperature, flow, salinity, photoperiod, and chemical signals (McDowall, 1988; Quinn, 2005).

Therefore, reproductive migration represents a close link between fish physiology, environmental conditions, and habitat connectivity.

Reproductive migration can be defined as the directed movement of fish from feeding, growing, or refuge habitats to specific breeding or spawning areas in order to reproduce successfully. This movement allows mature individuals to reach habitats where eggs can be released, fertilized, incubated, and developed under favorable environmental conditions (Lucas and Baras, 2001).

In reproductive migration, the destination is usually more important than the distance travelled. Some fish may migrate only a short distance within a river or lake, whereas others may travel hundreds or thousands of kilometres between marine and freshwater habitats. The essential feature is that the movement increases the probability of successful spawning and survival of the next generation.

2. IMPORTANCE OF MIGRATION FOR REPRODUCTION

“Migration for reproduction provides several biological advantages. First, it enables fish to reach spawning grounds that offer suitable physical and chemical conditions, such as appropriate temperature, oxygen concentration, water flow, substrate type, and salinity. These factors strongly influence fertilization success, egg development, and larval survival.

Second, reproductive migration helps separate spawning areas from adult feeding habitats. This separation may reduce competition between adults and juveniles and may also lower predation pressure on eggs and larvae. In many species, spawning habitats such as gravel beds, floodplains, estuaries, or offshore marine areas provide conditions that are more favorable for early life stages than adult habitats [1, 3].

Third, migration contributes to population connectivity and genetic exchange. When individuals move between habitats or return to particular spawning areas, they influence the structure, distribution, and persistence of fish populations. In species such as Pacific salmon, homing to natal streams is an important reproductive behavior that shapes population structure and local adaptation [4].

Finally, reproductive migration has ecological and economic importance. Migratory fish support aquatic food webs, transfer nutrients between ecosystems, and sustain commercial, recreational, and subsistence fisheries. Disruption of reproductive migration can therefore reduce recruitment, weaken fish populations, and affect both ecosystem stability and human livelihoods.

2.1. Reproductive Purpose of Fish Migration

Fish migration for reproduction is primarily an adaptive strategy that allows mature individuals to reach habitats where spawning success and early-life survival are maximized. In many species, adult feeding habitats are not suitable for egg development or larval growth. As a result, fish migrate to environments that provide appropriate physical, chemical, and ecological conditions for reproduction. The reproductive purpose of migration is therefore closely linked with spawning site selection, protection of early developmental stages, completion of complex life cycles, and maintenance of genetic diversity (Harden Jones, 1968; Lucas and Baras, 2001).

3. SPAWNING SITE SELECTION

Spawning site selection is one of the most important reasons for reproductive migration. Fish do not usually reproduce in random locations; instead, they select habitats that increase the probability of fertilization, egg survival, and larval development. Suitable spawning grounds may include gravel.

4. SCOPE OF THE CHAPTER

This chapter focuses on fish migration specifically in relation to reproduction. It discusses the reproductive purpose of migration, the main types of spawning related migration, the biological and environmental cues that guide migrating fish, and the physiological adaptations required for successful movement between habitats (Figure 1). The chapter also examines major examples such as salmon, European eel, sturgeon, and tuna, which represent different reproductive migration strategies.

In addition, the chapter considers the major threats to reproductive migration, including dams, habitat fragmentation, climate change, pollution, and overfishing during spawning periods. Conservation approaches such as fish passages, river restoration, protection of spawning grounds, seasonal fishing bans, and international management are also reviewed. The overall aim is to explain how reproductive migration supports fish population sustainability and why maintaining migration routes is essential for aquatic conservation.

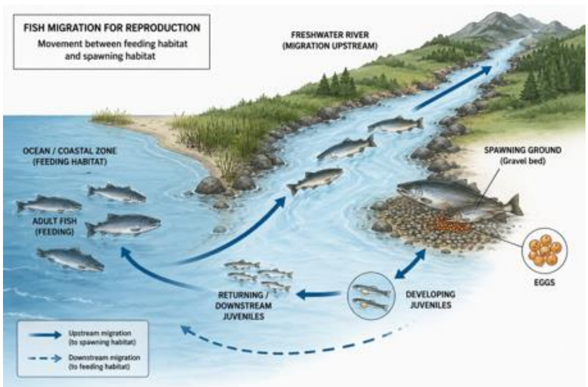

Figure 1. General concept of fish migration for reproduction, showing movement from feeding or growing habitats to spawning grounds.

5. REPRODUCTIVE PURPOSE OF FISH MIGRATION

Fish migration for reproduction is primarily an adaptive strategy that allows mature individuals to reach habitats where spawning success and early-life survival are maximized. In many species, adult feeding habitats are not suitable for egg development or larval growth. As a result, fish migrate to environments that provide appropriate physical, chemical, and ecological conditions for reproduction. The reproductive purpose of migration is therefore closely linked with spawning site selection, protection of early developmental stages, completion of complex life cycles, and maintenance of genetic diversity (Harden Jones, 1968; Lucas and Baras, 2001).

5.1. Spawning Site Selection

Spawning site selection is one of the most important reasons for reproductive migration (Figure 2).. Fish do not usually reproduce in random locations; instead, they select habitats that increase the probability of fertilization, egg survival, and larval development. Suitable spawning grounds may include gravel beds in rivers, floodplains, estuaries, coastal waters, coral-associated habitats, or offshore marine areas, depending on the species and its reproductive strategy. The quality of a spawning site is determined by several environmental factors, including water temperature, dissolved oxygen, flow velocity, substrate type, salinity, depth, and protection from predators. For example, many salmonids require clean, well-oxygenated gravel beds where eggs can be buried and protected during incubation. In contrast, some marine fishes migrate to offshore or pelagic spawning grounds where currents may help disperse eggs and larvae to nursery areas. Spawning migration also allows fish to synchronize reproduction with favorable seasonal conditions. Rainfall, river discharge, temperature changes, and photoperiod may act as cues that guide mature fish toward breeding areas. This synchronization is important because the survival of eggs and larvae often depends on the availability of suitable temperature, oxygen, shelter, and food resources at the correct time (Harden Jones, 1968; Lucas and Baras, 2001; Quinn, 2005).

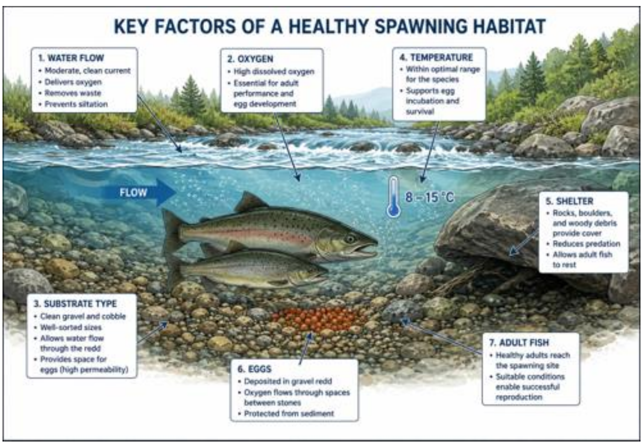

Figure 2. Major environmental factors influencing spawning site selection in migratory fishes

5.2. Egg And Larval Survival

A major reproductive benefit of migration is the improvement of egg and larval survival. Early life stages of fish are usually more vulnerable than adults because eggs and larvae have limited mobility, weak defense mechanisms, and narrow environmental tolerances. By migrating to suitable spawning grounds, adult fish place their offspring in habitats where survival conditions are relatively favorable.

Egg survival depends strongly on environmental stability. Adequate dissolved oxygen, suitable temperature, low sedimentation, and proper substrate are essential for embryonic development. Excessive siltation, poor water quality, extreme temperature, or low oxygen can reduce hatching success. In river-spawning species, eggs deposited in gravel beds may benefit from continuous water flow, which supplies oxygen and removes metabolic waste (Quinn, 2005).

Larval survival is also influenced by food availability, predation pressure, and transport to nursery habitats. In some species, currents help carry larvae from spawning grounds to areas where feeding conditions are suitable. In others, migration to floodplains, estuaries, or sheltered freshwater habitats provides larvae and juveniles with abundant food and reduced exposure to predators. Therefore, reproductive migration does not only support spawning itself; it also improves the chances that offspring will survive beyond the earliest developmental stages (Harden Jones, 1968; Lucas and Baras, 2001).

5.3. Completion of Life Cycle

For many migratory fishes, movement between habitats is essential for completing the life cycle. These species depend on different environments at different developmental stages. Adults may feed and grow in one habitat, while spawning and early development occur in another. Without migration, such species may be unable to reproduce successfully.

Diadromous fishes provide some of the clearest examples. Anadromous species, such as salmon, grow mainly in the marine environment but return to freshwater to spawn. Their life cycle depends on successful movement from freshwater nursery habitats to the ocean and later from the ocean back to natal or suitable spawning rivers. Catadromous species, such as freshwater eels, show the reverse pattern: they grow in freshwater or coastal areas and migrate to the sea for reproduction (McDowall,1988).

This separation of habitats can be advantageous because each environment supports a different life-history function. Feeding habitats may provide abundant resources for growth, while spawning habitats may provide safer or more suitable conditions for egg and larval development. However, this strategy also makes migratory fishes highly dependent on habitat connectivity. Barriers such as dams, degraded rivers, blocked estuaries, and altered flow regimes can interrupt the life cycle by preventing adults from reaching spawning grounds or juveniles from reaching feeding habitats.

5.4. Genetic Exchange

Reproductive migration also contributes to genetic exchange and population persistence. When fish move between habitats or spawning areas, they can connect populations that might otherwise be-come isolated. This movement may help maintain genetic diversity, reduce inbreeding, and improve the adaptive potential of populations under changing environmental conditions (Lucas and Baras, 2001)

However, the relationship between migration and genetic structure is complex. Some species show strong homing behavior, returning to the same river or spawning area where they were born. Pacific salmon are a well-known example, as natal homing can produce locally adapted populations that are genetically distinct from one another (Quinn, 2005). In such cases, reproductive migration supports both population structure and local adaptation.

In other species, individuals may mix across wider spawning areas, increasing gene flow among populations. This can be beneficial because it spreads genetic variation and may improve resilience to environmental change. Therefore, reproductive migration plays a dual role: it can maintain connectivity among populations while also allowing local adaptation where homing behavior is strong.

Overall, the reproductive purpose of fish migration is not limited to reaching a breeding site. It supports the entire reproductive process, from spawning-site selection to offspring survival, life-cycle completion, and maintenance of genetic diversity. These functions make reproductive migration essential for the long-term sustainability of many fish populations (Lucas and Baras, 2001).

6. TYPES OF FISH MIGRATION RELATED TO REPRODUCTION

Fish migration associated with reproduction can occur across different aquatic environments. Some species move between freshwater and marine habitats, while others migrate entirely within rivers, lakes, or oceans. The direction and purpose of movement depend on the species' life-history strategy, spawning requirements, and the environmental conditions needed for egg and larval development. The major migration types related to reproduction include anadromous, catadromous, potamodromous, oceanodromous, and, to a lesser extent, amphidromous migration (Table 1, Figure 3) (Harden Jones, 1968; Mcdowall, 1988; Lucas and Baras, 2001).

6.1. Anadromous Migration

Anadromous migration occurs when fish spend most of their adult life in the sea but migrate to freshwater to reproduce. This type of migration is strongly associated with spawning because mature adults must return to rivers or streams where eggs can be deposited and incubated. Anadromous fishes often use freshwater habitats as spawning and nursery areas, while marine habitats provide greater food availability for growth and maturation (Mcdowall, 1988; Lucas and Baras, 2001).

Salmon are among the best-known examples of anadromous fish. Many salmon species hatch in freshwater, migrate to the ocean for feeding and growth, and later return to freshwater rivers to spawn. Their return migration is often guided by environmental cues such as river flow, temperature, olfactory signals, and possibly geomagnetic information. In many salmonids, spawning takes place in gravel beds where eggs are buried and protected during incubation.

Anadromous migration provides reproductive advantages, but it also creates dependence on connected river–ocean systems. If adults cannot reach spawning grounds due to dams, blocked rivers, or degraded habitats, reproduction may fail. Therefore, maintaining access between marine feeding areas and freshwater spawning sites is essential for anadromous species (Quinn, 2005).

6.2. Catadromous Migration

Catadromous migration is the reverse of anadromous migration. In this pattern, fish spend most of their growth phase in freshwater or coastal habitats but migrate to the sea to reproduce. The reproductive phase therefore depends on successful movement from inland or nearshore habitats to marine spawning areas.

Freshwater eels are the most widely recognized catadromous fishes. The European eel, *Anguilla anguilla*, grows in freshwater rivers, lakes, estuaries, and coastal waters, but mature adults migrate to the Sargasso Sea for spawning. After reproduction, larvae drift with ocean currents toward continental waters, where they later enter coastal and freshwater habitats as juveniles.

Catadromous migration shows how reproduction may depend on distant marine habitats even when most of the adult life is spent in freshwater. This strategy requires long-distance navigation, physiological adjustment to changing salinity, and successful larval transport by ocean currents. Disruption at any stage of this route can reduce recruitment and weaken population recovery (Mcdowall, 1988).

6.3. Potamodromous Migration

Potamodromous migration occurs entirely within freshwater systems. Fish may move within rivers, between rivers and floodplains, or between lakes and connected streams to reach suitable spawning habitats. Although these migrations may be shorter than ocean-linked migrations, they are often essential for reproduction .

Many freshwater fishes migrate upstream or into floodplain habitats during the breeding season. These movements may be triggered by rainfall, increased river discharge, temperature changes, or seasonal flooding. Spawning in floodplains or shallow river margins can provide eggs and larvae with warmer water, abundant food, vegetation cover, and reduced predation pressure.

Examples of potamodromous fishes include several carp, catfish, sturgeon, and riverine species. In large river systems, potamodromous migration can be highly vulnerable to dams, channel modification, water abstraction, and floodplain disconnection. Even when migration occurs entirely within freshwater, reproductive success depends on habitat connectivity and natural flow patterns (Lucas and Baras, 2001).

6.4. Oceanodromous Migration

Oceanodromous migration occurs entirely within marine environments. In this type of migration, fish move between different oceanic areas for feeding, growth, and reproduction. When related to re-production, oceanodromous migration allows adults to reach spawning grounds where temperature, currents, food availability, and larval dispersal conditions are suitable.

Tuna are important examples of oceanodromous fishes. Many tuna species undertake large-scale movements across ocean basins and may migrate to specific spawning areas in warm waters. These migrations are influenced by ocean temperature, prey distribution, currents, and reproductive condition. Spawning often occurs in areas where environmental conditions support egg buoyancy, larval survival, and early feeding

Oceanodromous reproductive migration is difficult to conserve because routes and spawning grounds may cross international waters and the exclusive economic zones of several countries. For this reason, management of oceanodromous species often requires international cooperation, stock assessment, and regulation of fishing pressure during breeding periods (Harden-Jones, 1968; Lucas and Baras, 2001).

6.7. Amphidromous Migration

Amphidromous migration involves movement between freshwater and marine environments, but unlike anadromous and catadromous migration, the movement is not primarily for spawning. In many amphidromous species, adults spawn in freshwater, larvae drift downstream to the sea, and juveniles later return to freshwater to grow. Therefore, amphidromy is indirectly related to reproduction because early-life dispersal and juvenile recruitment depend on movement between habitats.

Some gobies and other small tropical stream fishes show amphidromous life cycles. Spawning may occur in freshwater streams, but larvae are transported to marine or estuarine environments, where they develop before returning upstream as juveniles. This strategy allows larvae to use productive coastal waters while adults occupy freshwater habitats.

Although amphidromous migration is not a spawning migration in the strict sense, it remains important for reproductive success because offspring survival depends on access between rivers and the sea. Barriers near river mouths, altered stream flow, pollution, and coastal habitat degradation can interfere with larval transport and juvenile return migration (Mcdowall, 1988; Lucas and Baras, 2001).

Table 1. Major types of fish migration related to reproduction.

Migration Type	Movement Pattern	Reproductive Relevance	Example
Anadromous	Sea to freshwater	Adults migrate to freshwater to spawn	Salmon
Catadromous	Freshwater or coastal habitats to sea	Adults migrate to marine spawning areas	European eel
Potamodromous	Within freshwater	Adults migrate to rivers, floodplains, or streams for spawning	Carp, sturgeon
Oceanodromous	Within marine environments	Adults migrate to oceanic spawning grounds	Tuna
Amphidromous	Between freshwater and sea, not mainly for spawning	Larval dispersal and juvenile recruitment depend on habitat movement	Gobies

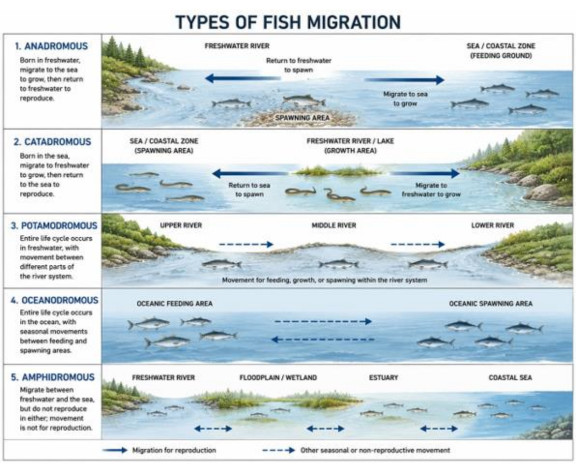

Figure 3. Main types of fish migration related to reproduction and early-life development.

7. BIOLOGICAL AND ENVIRONMENTAL CUES

Reproductive migration in fishes is regulated by a combination of internal physiological condition and external environmental cues (Figure 4). Mature individuals do not begin migration randomly; rather, migration usually occurs when reproductive readiness coincides with suitable environmental conditions.

Important cues include temperature, water flow, rainfall, salinity, chemical signals, geomagnetic information, and seasonal changes in light. These factors help fish determine when to migrate, which route to follow, and where to spawn (Harden-Jones, 1968; Lucas and Baras, 2001; Ordeix et all, 2024).

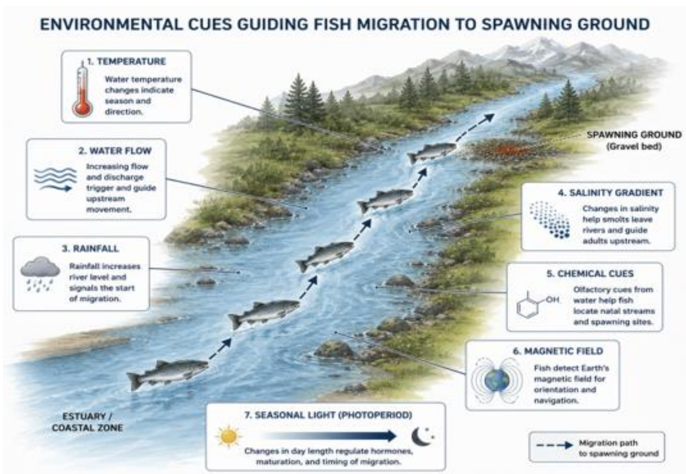

Figure 4. Major biological and environmental cues involved in reproductive migration of fish

7.1. Temperature

Water temperature is one of the most important environmental cues influencing reproductive migration. Temperature affects metabolism, gonadal development, swimming performance, and the timing of spawning. In many species, migration begins when water temperature reaches a suitable seasonal range for reproductive activity and egg.

The importance of temperature is particularly clear in river-spawning fishes. If water is too cold, reproductive development and egg incubation may be delayed; if it is too warm, adults may experience physiological stress and eggs may suffer reduced survival. Therefore, temperature acts both as a trigger for migration and as a limiting factor for reproductive success. Climate-driven changes in water temperature can alter migration timing and may create a mismatch between spawning activity and optimal conditions for offspring survival. development (Lucas and Baras 2001; Ordeix, et al. 2024).

7.2. Water Flow and Rainfall

Water flow and rainfall are major cues for reproductive migration, especially in freshwater and anadromous fishes. Increased river discharge after rainfall can stimulate upstream migration by improving passage conditions, increasing water depth, and carrying chemical signals from spawning habitats downstream. In seasonal rivers and floodplain systems, rainfall and rising water levels may also provide access to temporary spawning and nursery habitats.

Flow conditions are particularly important because they influence both adult migration and early-life survival. Moderate current can help guide fish toward spawning areas, oxygenate eggs, and remove metabolic waste from incubation sites. However, abnormal flow patterns caused by dams, water abstraction, or altered rainfall may disrupt migration timing and reduce spawning success. Thus, natural flow regimes are essential for many species that depend on seasonal reproductive migration (Lucas and Baras 2001; Ordeix, et al. 2024).

7.3. Salinity

Salinity is an important cue for fishes that migrate between freshwater and marine environments. Anadromous and catadromous species must detect and tolerate changes in salinity as they move between rivers, estuaries, coastal waters, and the open ocean. These changes are closely linked with osmoregulation, which allows fish to maintain water and ion balance in different aquatic environments.

In reproductive migration, salinity gradients can help guide movement through estuaries and transitional waters. For example, anadromous fishes moving from the sea into freshwater must physiologically prepare for low-salinity conditions before reaching spawning rivers. Catadromous fishes show the opposite pattern, moving from freshwater or coastal habitats toward marine spawning areas. Successful migration therefore depends not only on navigation, but also on the ability to adjust physiologically to changing salinity conditions (Mcdowall, 1988; Lucas and Baras, 2001).

7.4. Chemical Cues

Chemical cues are especially important during the final stages of reproductive migration. Many fishes use olfactory information to recognize specific habitats, avoid unsuitable areas, and locate spawning grounds. Salmonids provide the clearest example: adult salmon are able to return to their natal streams using chemical signatures learned during earlier life stages.

Chemical cues may originate from the physical and biological characteristics of a river, including dissolved organic compounds, minerals, and other habitat-specific signals. These cues allow migrating fish to distinguish between different tributaries and spawning locations. In species with strong homing behavior, chemical recognition helps maintain population structure because individuals repeatedly return to particular breeding sites. However, pollution or changes in water chemistry can interfere with olfactory navigation and may reduce the accuracy of homing (Quinn, 2005; Ueda, 2014).

7.5. Magnetic Cues

Magnetic cues may assist long-distance navigation in some migratory fishes, particularly during oceanic phases when local chemical cues are unavailable. Research on salmon has suggested that geomagnetic information may help fish orient across large spatial scales before they use olfactory cues near the spawning river. This mechanism is often described as geomagnetic imprinting, where fish may learn magnetic characteristics of a location and later use them during migration.

Magnetic navigation is not expected to replace other cues; rather, it likely works together with additional sensory information. For example, magnetic cues may help guide fish toward a broad coastal region, while chemical cues may guide final river selection. This combination of long-distance and short-distance cues is important because reproductive migration often requires accurate movement across complex and changing aquatic environments (Putman, et al., 2014; Ueda, 2014).

7.6. Seasonal Light Changes

Seasonal changes in day length, or photoperiod, help regulate reproductive timing in many fishes. Unlike temperature and rainfall, photoperiod follows a predictable annual pattern and can provide a reliable seasonal signal. Changes in light duration can influence endocrine activity, gonadal development, and the timing of migration.

Photoperiod is particularly important because reproductive migration must often be synchronized with seasonal environmental conditions. For example, migration may need to occur before spawning habitats become suitable or before larvae require abundant food resources. In this way, seasonal light changes help prepare fish physiologically before migration begins, while local cues such as temperature, flow, and chemical signals may refine the exact timing and route of movement. Overall, reproductive migration is controlled by multiple interacting cues rather than by a single factor. Temperature, flow, salinity, chemical signals, magnetic information, and photoperiod each contribute to migration timing, orientation, and spawning success. The relative importance of each cue varies among species, habitats, and life-history strategies, but together they ensure that reproduction occurs in suitable places and at appropriate times (Lucas and Baras ,2001; Zydlewski et al., 2014).

8. PHYSIOLOGICAL ADAPTATIONS

Reproductive migration requires major physiological adjustments because migrating fish must move through changing environments while also preparing for spawning (Figure 5). These adjustments include regulation of water and ion balance, storage and use of energy reserves, endocrine control of reproductive development, sustained swimming performance, and visible changes in body form or colour. The intensity of these adaptations differs among species, but they are especially clear in long-distance migratory fishes such as salmon and eels (Lucas and Baras 2001; McCormick, 2001; Mommsen, 2004).

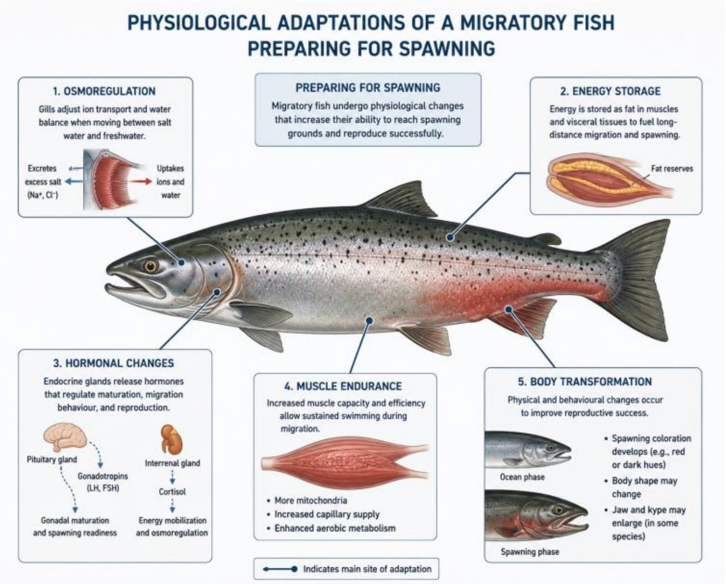

Figure 5. Main physiological adaptations supporting fish migration for reproduction.

8.1. Osmoregulation

Osmoregulation is the process by which fish maintain internal water and ion balance despite changes in environmental salinity. This adaptation is particularly important for diadromous fishes that migrate between freshwater and seawater. In freshwater, fish tend to gain water and lose ions, whereas in seawater they tend to lose water and gain salts. Successful reproductive migration therefore requires the gills, kidneys, intestine, and endocrine system to adjust before and during movement between habitat

In anadromous species such as salmon, adults returning from the ocean must regain freshwater tolerance before entering rivers to spawn. In catadromous species such as eels, maturing individuals must prepare for movement from freshwater or coastal habitats into seawater. These changes are regulated by hormones, including cortisol, prolactin, growth hormone, and insulin-like growth factor

I. Cortisol and growth hormone are generally associated with seawater adaptation, while prolactin is important in freshwater adaptation.

Osmoregulatory failure can reduce migration success because fish may experience dehydration, ion imbalance, stress, or reduced swimming ability. Therefore, osmoregulation is not only a survival mechanism but also a prerequisite for successful reproductive migration in species moving across salinity gradients (McDowall, 1988; McCormick, 2001).

8.2. Energy Storage

Long-distance reproductive migration requires substantial energy reserves. Many migratory fishes accumulate lipids and proteins before migration, which are later used to support swimming, gonadal development, and spawning behavior. This is especially important in species that reduce or stop feeding during migration.

Pacific salmon provide a clear example. Adult salmon generally stop feeding after entering freshwater and rely on stored energy to complete upstream migration, develop reproductive tissues, compete for mates, construct nests, and spawn. As migration progresses, lipid reserves are depleted first, while proteins from muscle may also be mobilized during the final stages of migration and reproduction.

Energy storage influences reproductive success because individuals with insufficient reserves may fail to reach spawning grounds or may have reduced spawning performance. Migration distance, river temperature, current velocity, and obstacles such as dams can increase energetic cost. Therefore, the amount and quality of stored energy before migration can strongly affect survival and reproductive output Brett,1995; Mommsen, 2004).

8.3. Hormonal Changes

Hormonal regulation coordinates migration, maturation, osmoregulation, and spawning. During reproductive migration, endocrine signals control gonadal development, secondary sexual characteristics, stress responses, and behavioral changes. These hormonal changes allow the fish to shift from feeding and growth toward reproduction.

Gonadal hormones such as estrogens and androgens are involved in the development of eggs, sperm, and reproductive behavior. Cortisol also plays an important role, particularly in salmonids, where it is associated with stress physiology, osmoregulation, and changes occurring during home-stream migration and spawning. Carruth et al. (2002) reported that Pacific salmon show strong physiological and tissue changes during home-stream migration, with these changes associated with elevated plasma cortisol.

Hormonal changes must be properly timed. If endocrine development occurs too early or too late, migration and spawning may become mismatched with environmental conditions. This timing is especially important where temperature, flow, salinity, and photoperiod influence both migration cues and reproductive readiness (McCormick, 2001; Carruth, et al. 2002).

8.4. Muscle Endurance

Sustained swimming is essential for reproductive migration. Migrating fish may need to travel long distances, overcome currents, pass through estuaries, avoid predators, and reach spawning sites under variable environmental conditions. Muscle endurance is therefore a key physiological adaptation, particularly in species that migrate upstream or across large marine areas.

Fish use both aerobic and anaerobic muscle systems during migration. Aerobic metabolism supports prolonged swimming over long distances, while anaerobic metabolism may be used during short bursts of intense activity, such as passing rapids, avoiding predators, or competing for spawning sites. Efficient oxygen transport, cardiovascular performance, and muscle metabolism are therefore necessary for successful migration. ((Lucas and Baras 2001; Brett,1995)

In salmon, the energetic demand of migration is closely linked with muscle metabolism. During prolonged fasting and migration, muscle tissue may serve not only for locomotion but also as an energy source for reproduction. Mommsen (2004) described salmon spawning migration as a useful model for understanding muscle protein metabolism during prolonged migration and starvation. This highlights the physiological cost of reaching spawning grounds.

8.5. Body Transformation

Many fishes undergo body transformations during reproductive migration. These changes may include alterations in body color, shape, jaw structure, skin thickness, scale condition, and development of secondary sexual characters. Such changes are usually associated with sexual maturation, mate attraction, competition, nest construction, or spawning behavior.

In Pacific salmon, body transformation during spawning migration can be highly visible. Adults may develop brighter coloration, hooked jaws, enlarged teeth, or a deeper body form depending on the species and sex. These traits can improve reproductive success by supporting mate competition, territory defense, or sexual signaling. However, they may also increase energetic cost and physical stress. Body transformation often occurs alongside reduced feeding, depletion of energy reserves, and hormonal changes. Therefore, it should not be viewed as a cosmetic change only; it is part of the broader physiological shift from growth and survival toward reproduction. In semelparous species such as many Pacific salmon, these changes are extreme because adults invest nearly all remaining resources into a single reproductive event (Quinn, 2005; Carruth et al.,2002)

9.EXAMPLES OF FISH MIGRATION FOR REPRODUCTION

9.1. Examples of Fish Migration for Reproduction

Reproductive migration is expressed differently among fish species depending on their habitat use, spawning requirements, and life-history strategy. Some species migrate from the sea to freshwater, some move from freshwater to the sea, while others migrate within rivers or oceans. The following examples illustrate four major reproductive migration patterns: salmon, European eel, sturgeon, and tuna (Table 2, Figure 6).

Table 2. Examples of fish migration for reproduction.

Species/Group	Migration Type	Reproductive Route	Main Spawning Habitat
Salmon	Anadromous	Ocean to freshwater rivers	Gravel beds in rivers and streams
European eel	Catadromous	Freshwater/coastal waters to the Sargasso Sea	Oceanic spawning area
Sturgeon	Anadromous or potamodromous	Coastal/lower river habitats to upstream river areas	Flowing freshwater with hard substrate
Tuna	Oceanodromous	Feeding areas to marine spawning grounds	Warm oceanic waters

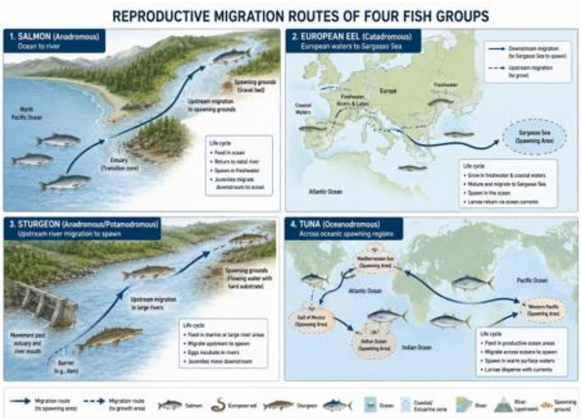

Figure 6. Representative reproductive migration routes of salmon, European eel, sturgeon, and tuna.

9.2. Salmon

Salmon are among the most widely studied examples of anadromous reproductive migration. They hatch in freshwater, migrate to the ocean for feeding and growth, and later return to freshwater rivers to spawn. This return migration is strongly linked with natal homing, where adults often return to the same river or stream in which they hatched.

The reproductive migration of salmon provides several advantages. Freshwater gravel beds offer suitable conditions for egg deposition, incubation, and protection. Female salmon construct nests, known as redds, in gravel substrates where eggs are buried after fertilization. Clean, well-oxygenated water is essential because embryos develop within the gravel until hatching. After emergence, juveniles remain in freshwater for a period before migrating toward the sea, depending on the species and population.

Salmon migration is controlled by several environmental and biological cues, including river flow, temperature, olfactory signals, and physiological maturation. However, the same migration route also exposes adults to high energetic costs and environmental barriers. Dams, warming river temperatures, sedimentation, and habitat degradation can reduce access to spawning grounds and lower reproductive success. Therefore, salmon are a useful model for understanding how habitat connectivity supports reproductive migration (Quinn, 2005).

9.3. European Eel

The European eel, *Anguilla anguilla*, is a classic example of catadromous reproductive migration. Unlike salmon, European eels grow in freshwater, estuarine, or coastal habitats but migrate to the ocean to reproduce. Mature silver eels leave continental waters and migrate across the Atlantic Ocean toward the Sargasso Sea, which is considered their main spawning area (McDowall, 1988; Righton, et al., 2016; Wright, et al., 2022).

This migration is remarkable because it covers several thousand kilometres and occurs mostly in the open ocean. Tracking studies have shown that European eels undertake long-distance oceanic movements during their spawning migration, although many details of the exact route, spawning behavior, and adult fate remain difficult to observe directly (Righton, et al., 2016; Wright, et al., 2022). After spawning, eel larvae, known as leptocephali, are transported by ocean currents toward European and North African continental waters, where they later develop into glass eels and enter coastal or freshwater habitats. The reproductive migration of European eel demonstrates the importance of connectivity be-tween inland waters, estuaries, coastal zones, and oceanic spawning areas. Barriers to downstream migration, turbine mortality, pollution, overfishing, parasites, and changes in oceanic conditions may all reduce recruitment. Because the species has a complex life cycle across international waters, its conservation requires coordinated management across multiple regions.

9.4. Sturgeon

Sturgeons are ancient fishes with reproductive migrations that are often associated with large river systems. Many sturgeon species are anadromous or potamodromous, moving from coastal or lower river habitats to upstream freshwater spawning grounds. Atlantic sturgeon, *Acipenser oxyrinchus oxyrinchus*, for example, spend much of their adult life in marine or estuarine environments but migrate into freshwater rivers to spawn.

Sturgeon typically require specific riverine spawning habitats with flowing water and suitable hard substrates such as gravel, cobble, or rocky bottoms. Their reproductive strategy is characterized by late maturity, long lifespan, large body size, and intermittent spawning. In Atlantic sturgeon, males and females do not necessarily spawn every year, and females may return to spawn only after several years. This makes population recovery slow when adult numbers are reduced. Reproductive migration in sturgeon is highly vulnerable to human disturbance. Dams can block access to historical spawning grounds, while dredging, river modification, water withdrawal, pollution, and bycatch can reduce survival. Because sturgeon populations depend on successful adult return and suitable spawning habitat, protecting river connectivity and spawning areas is essential for their conservation (NOAAF, 2026).

9.5. Tuna

Tuna represent oceanodromous reproductive migration because their movements occur entirely within marine environments. Unlike salmon, eels, or many sturgeons, tuna do not need freshwater habitats for reproduction. Instead, they migrate across oceanic regions to reach suitable spawning areas where temperature, currents, and food-web conditions support egg and larval survival Harden-Jones, 1968; Lucas and Baras, 2001) Atlantic bluefin tuna, *Thunnus thynnus*, is a major example. The species is highly migratory and has traditionally been associated with two main spawning regions: the Gulf of Mexico for the western stock and the Mediterranean Sea for the eastern stock. More recent research has also provided evidence of spawning activity in the Slope Sea, indicating that reproductive habitat use may be broader than previously assumed.

Tuna spawning migration is closely linked with warm-water conditions and reproductive readiness. Adults may travel long distances between feeding grounds and spawning areas, and spawning generally occurs in waters suitable for egg buoyancy and larval development. However, tuna reproductive migration is strongly affected by fishing pressure because adults are often targeted during seasonal movements and spawning aggregations. Effective management therefore requires international cooperation, monitoring of spawning areas, and regulation of fishing mortality (Richardson, et al., 2016).

10. ENVIRONMENTAL THREATS TO REPRODUCTIVE MIGRATION

10.1. Environmental Threats to Reproductive Migration

Reproductive migration depends on the ability of fish to move between feeding, growing, and spawning habitats at the correct time. Environmental disturbance can interrupt this process by blocking migration routes, altering migration cues, degrading spawning habitats, or reducing the number of mature adults that reach breeding areas. The main threats to reproductive migration include dams and barriers, climate change, pollution, habitat destruction, and overfishing during spawning periods (Table 3, Figure 7) (Dudgeon et al., 2006; Liermann, et al., 2012).

Table 3. Major environmental threats to reproductive migration in fishes

Threat	Main Effect on Migration	Impact on Reproduction
Dams and barriers	Block or delay movement to spawning grounds	Reduced spawning access and lower recruitment
Climate change	Alters temperature, flow, rainfall, and ocean conditions	Mismatch between spawning time and suitable egg or larval conditions
Pollution	Causes toxicity, stress, and impaired navigation	Reduced fertility, egg survival, and larval development
Habitat destruction	Removes or degrades spawning and nursery habitats	Loss of breeding sites and reduced juvenile survival
Overfishing during spawning migration	Removes mature adults before reproduction	Lower spawning biomass and reduced recruitment

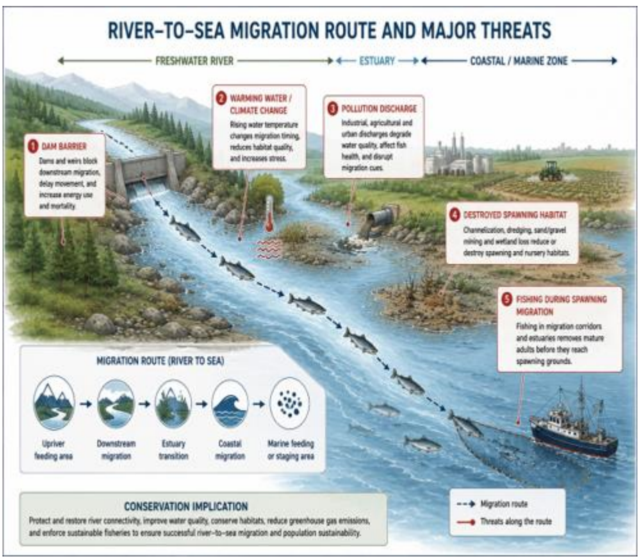

Figure 7. Environmental threats affecting fish migration for reproduction

10.2. Dams and Barriers

Dams, weirs, culverts, and other artificial barriers are among the most direct threats to reproductive migration. They can prevent adult fish from reaching spawning grounds and can also block the downstream movement of eggs, larvae, juveniles, or post-spawning adults. This is especially serious for anadromous and potamodromous species that require access to upstream river habitats for reproduction.

Barriers do not only block movement; they also change river flow, sediment transport, water temperature, and habitat structure. These changes can reduce the quality of spawning grounds even when fish passages are present. For example, altered flow below dams may reduce the seasonal discharge cues that normally stimulate migration, while sediment trapping may limit the formation of gravel beds required by many river-spawning fishes.

Fish ladders and bypass systems can reduce the impact of barriers, but their effectiveness varies among species, body sizes, swimming abilities, and river conditions. Therefore, barrier management should not focus only on passage construction; it should also consider environmental flow, habitat quality, and the full reproductive route of the target species (Liermann et al., 2012).

10.3. Climate Change

Climate change affects reproductive migration mainly through rising water temperature, altered rainfall patterns, modified river discharge, and changes in ocean conditions. Since many fishes rely on temperature, flow, and seasonal cues to begin migration and spawning, climate change can shift the timing of reproductive movements and reduce synchronization between spawning and suitable environmental conditions.

Higher water temperature can increase metabolic demand and physiological stress during migration. It may also reduce dissolved oxygen and narrow the thermal window suitable for egg development. In some species, adults may migrate earlier or later than usual, but spawning habitats may not provide optimal conditions for embryo and larval survival at those altered times.

Climate change can also affect marine reproductive migrants such as tuna and eels by changing ocean currents, productivity, prey availability, and larval transport. For freshwater and diadromous fishes, droughts, floods, and irregular river flows can reduce access to spawning grounds or destroy eggs after deposition. Thus, climate change threatens both the timing and success of reproductive migration (Ficke, et al., 2007).

10.4. Pollution

Pollution can interfere with reproductive migration through direct toxicity, physiological stress, impaired navigation, and reduced reproductive performance. Common pollutants include industrial effluents, agricultural pesticides, heavy metals, petroleum hydrocarbons, plastics, and excess nutrients. These contaminants can affect adult migrants, developing eggs, larvae, and the food webs that support early-life stages

Chemical pollution is particularly important because many migratory fishes depend on olfactory cues to locate spawning habitats. Changes in water chemistry may reduce the ability of fish to detect natal streams, avoid unsuitable habitats, or identify appropriate spawning areas. In addition, some contaminants can damage reproductive organs, disrupt endocrine function, reduce gamete quality, or lower hatching success.

Pollution also degrades spawning habitats indirectly. Nutrient enrichment can cause algal blooms and oxygen depletion, while suspended solids and toxic sediments can smother eggs deposited in gravel or benthic habitats. As a result, pollution can reduce reproductive success even when adult fish are still able to reach spawning grounds (Fleeger et al., 2003; Dudgeon et al., 2006).

10.5. Habitat Destruction

Habitat destruction reduces the availability and quality of spawning, nursery, and migration habitats. River channelization, dredging, deforestation, wetland drainage, mining, urban development, and agricultural expansion can remove or degrade the physical structures needed for successful re-production. These impacts are especially damaging when they affect spawning beds, floodplains, estuaries, or river margins used by eggs and juveniles.

For river-spawning fishes, habitat destruction often leads to loss of gravel beds, increased sedimentation, reduced bank vegetation, and simplified river channels. Fine sediment can fill spaces between gravel particles, reducing oxygen supply to buried eggs. Loss of riparian vegetation can increase water temperature and reduce shelter for juveniles. In floodplain systems, disconnection be-tween rivers and seasonal wetlands can prevent fish from accessing productive breeding and nursery areas.

Habitat destruction may also fragment populations. When spawning sites are lost or isolated, fish may be forced to use poorer habitats or may fail to reproduce. Over time, this can reduce recruitment, weaken population resilience, and increase the risk of local extinction (Dudgeon, et al., 2006).

10.6. Overfishing During Spawning Migration

Fish are often highly vulnerable during reproductive migration because adults may gather at predictable times and locations. Spawning runs and spawning aggregations can make fish easier to capture, particularly when fishing targets mature individuals before they have reproduced. This can sharply reduce spawning biomass and recruitment.

The effect of overfishing during spawning migration is not limited to reducing adult abundance. Removing large, mature individuals can also reduce egg production because larger females often produce more eggs and may produce eggs of higher quality. In species with delayed maturity, intermittent spawning, or long generation times, population recovery can be slow after heavy exploitation.

Seasonal fishing bans, protected spawning areas, gear restrictions, and catch limits are there-fore important tools for protecting reproductive migration. Management should aim to ensure that enough mature adults survive migration, reach spawning grounds, and reproduce before being exposed to fishing pressure (Mitcheson, et al., 2008; Erisman, et al., 2017).

11.CONSERVATION OF REPRODUCTIVE MIGRATION

Conservation of reproductive migration requires protection of both movement routes and spawning habitats. Since migratory fishes often depend on several connected habitats during their life cycle, management must address barriers, altered flows, habitat degradation, fishing pressure, and loss of genetic diversity. Effective conservation therefore combines engineering solutions, habitat restoration, fisheries regulation, hatchery management, and international cooperation (Lucas and Baras, 2001; Dudgeon, et al., 2006; Liermann, et al., 2012).

11.1. Fish Ladders and Fish Passages

Fish ladders and fish passages are structures designed to help fish move around dams, weirs, and other barriers. They are especially important for species that must migrate upstream to reach spawning grounds. Common designs include pool-and-weir fish ways, vertical-slot fish ways, nature-like bypass channels, fish lifts, and downstream bypass systems. For reproductive migration, the main purpose of fish passage is to reduce delay and mortality during movement to spawning areas. However, passage success varies among species because swimming ability, body size, behavior, and motivation differ. A passage system designed for salmon may not work equally well for weaker swimmers or bottom-oriented species. Recent reviews also show that fish way performance is often uneven across fish groups, emphasizing the need for species-specific design and monitoring.

Therefore, fish passages should not be treated as a complete solution by themselves. They are most effective when combined with environmental flow management, suitable entrance placement, downstream protection, and regular evaluation of passage efficiency (Katopodis and Williams, 2012).

11.2. Dam Removal and River Restoration

Dam removal is one of the most direct methods for restoring reproductive migration when a barrier is obsolete, unsafe, or no longer economically justified.

Removing a dam can reconnect upstream spawning habitats, restore natural flow, improve sediment transport, and allow migratory fish to recolonize previously inaccessible areas. Dam obstruction has been identified as a major driver of freshwater fish fragmentation and diversity loss.

River restoration is broader than dam removal. It may include restoring natural channel structure, reconnecting floodplains, improving riparian vegetation, increasing habitat complexity, and re-establishing environmental flow patterns. These actions are important because fish require not only access to spawning grounds but also suitable physical conditions for egg incubation and juvenile development. However, dam removal and restoration must be carefully planned. Sudden sediment release, invasive species spread, or changes in water quality can create short-term risks. For this reason, restoration projects should include baseline surveys, staged implementation where necessary, and long-term biological monitoring.

For reproductive migration conservation, hatcheries should not replace habitat protection. They should be treated as temporary or supportive tools within a broader recovery plan. Best practice includes using local broodstock, maintaining genetic diversity, minimizing domestication, screening for disease, marking released fish, and monitoring survival and reproductive contribution after release. (Liermann, et al., 2012).

11.3. Protection of Spawning Grounds

Protection of spawning grounds is essential because migration has little reproductive value if the destination habitat is degraded. Spawning areas may include gravel beds, floodplains, estuaries, wetlands, reefs, coastal zones, or offshore marine areas. These habitats must provide suitable substrate, oxygen, temperature, salinity, flow, and shelter for eggs and larvae.

Conservation measures may include protected areas, restrictions on dredging or sand mining, riparian buffer zones, pollution control, and prevention of destructive fishing in breeding habitats. FAO technical guidance emphasizes that critical fish habitats, including nursery and spawning areas, should be protected and rehabilitated as far as possible. This is especially important for species with narrow spawning requirements or strong fidelity to particular breeding sites.

Spawning-ground protection should also consider seasonal timing. Some habitats may need strict protection only during breeding periods, while others require year-round conservation because they support eggs, larvae, juveniles, and adult migrants at different times (FAO, 2008).

11.4 Seasonal Fishing Bans

Seasonal fishing bans are used to protect mature adults during migration and spawning. Many migratory fish become easier to catch when they gather in predictable places, such as river mouths, spawning rivers, coastal migration corridors, or marine spawning aggregations. Harvesting adults before reproduction can reduce spawning biomass and weaken recruitment.

A well-designed seasonal ban should be based on the reproductive calendar of the target species. It should cover the period when adults migrate, spawn, and, where necessary, recover after spawning. In addition, seasonal bans are most effective when combined with gear restrictions, catch limits, protected spawning areas, and enforcement against illegal fishing.

The main advantage of seasonal bans is that they allow fish to reproduce before being exposed to fishing pressure. This is particularly important for species with delayed maturity, long generation time, or low population resilience, such as many sturgeons and some large marine fishes (Mitcheson, et al., 2008; Erisman, et al., 2017).

11.5. Hatchery and Restocking Programs

Hatchery and restocking programs can support declining populations by producing juveniles for release into natural habitats. These programs may be useful when natural recruitment is very low, spawning habitats have been degraded, or populations are at immediate risk of local extinction. In such cases, hatcheries can provide demographic support while habitat restoration is being implemented.

However, hatchery programs must be used carefully. Poorly managed stocking can reduce genetic diversity, increase domestication selection, spread disease, and weaken local adaptation. Genetic risks are especially high when hatchery production depends on a small number of bloodstock or when hatchery-origin fish interbreed extensively with wild populations (Busack and Currens, 1995, Hedgecock and Coykendall, 2007).

11.6. International Cooperation

Many migratory fishes cross political boundaries during reproductive migration. Eels, tuna, salmon, sturgeons, and other migratory species may move through rivers, estuaries, coastal waters, exclusive economic zones, and international waters. As a result, conservation cannot be fully effective if management is limited to one country or one part of the migration route.

International cooperation is needed for shared stock assessment, catch regulation, protection of migration corridors, control of illegal fishing, and monitoring of spawning areas. For highly migratory marine species such as tuna, regional fisheries management organizations are central to coordinating conservation and fishing rules across countries. For diadromous species, cooperation is often required between inland, coastal, and marine authorities.

Effective international management should protect the complete reproductive pathway: adult feeding areas, migration routes, spawning grounds, larval transport zones, and juvenile habitats. Without this life-cycle approach, conservation actions in one region may be undermined by habitat loss or over exploitation in another (Table 4, Figure 8).

Table 4. Major conservation strategies for reproductive migration in fishes.

Conservation Strategy	Main Purpose	Reproductive Benefit
Fish ladders and passages	Allow fish to bypass migration barriers	Improves access to spawning grounds
Dam removal and river restoration	Reconnect fragmented rivers and restore natural habitat	Restores spawning routes and improves habitat quality
Protection of spawning grounds	Prevent degradation of breeding habitats	Increases egg, larval, and juvenile survival
Seasonal fishing bans	Reduce harvest during migration and spawning	Allows mature adults to reproduce before capture
Hatchery and restocking programs	Support depleted populations	Can increase juvenile numbers when natural recruitment is low
International cooperation	Coordinate management across migration routes	Protects species that cross national boundaries

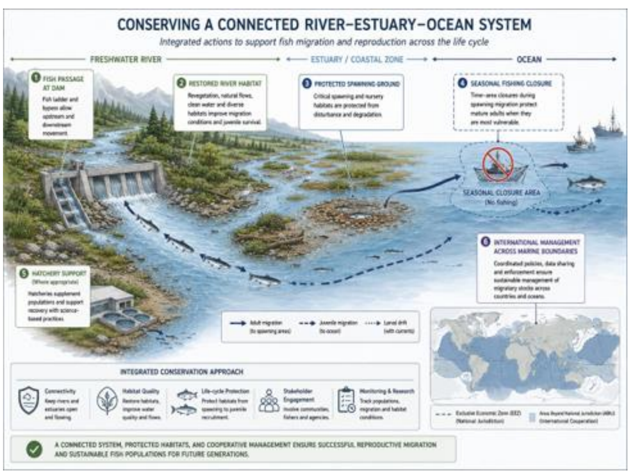

Figure 8. Conservation strategies supporting fish migration for reproduction.

12. COMPARATIVE CASE SYNTHESIS

The four focal groups show that reproductive migration is best understood as a linked pathway rather than as a single movement event. Salmon depend on access to natal freshwater spawning reaches; European eels require continuity from continental waters to the Sargasso Sea; sturgeons require adult survival and unobstructed access to riverine hard-bottom habitat; and tuna require management across wide marine areas and political boundaries. The conservation unit is therefore the complete reproductive pathway, including migration corridors, spawning habitat, and early-life nursery conditions (Table 5) (Quinn, 2005; Righton et al., 2016; Richardson et al., 2016; Wright, et al., 2022; NOAAF,2026).

Table 5. Comparison of reproductive migration strategies and conservation priorities

Group	Type	Reproductive habitat	Primary vulnerability	Priority action
Salmon	Anadromous	Freshwater gravel beds	Barriers, warming rivers, sedimentation	Restore connectivity and spawning habitat
European eel	Catadromous	Sargasso Sea	Barriers, harvest, turbines, ocean change	Manage the full inland–ocean life cycle
Sturgeon	Anadromous or potamodromous	Flowing rivers with hard substrate	Adult mortality, dams, late maturity	Protect adults and reopen spawning routes
Tuna	Oceanodromous	Warm marine spawning areas	Fishing pressure and shifting habitat	Coordinate international stock management

The comparison also exposes a management blind spot: passage counts or catch statistics alone do not demonstrate reproductive recovery. Effective monitoring should measure arrival at spawning habitat, spawning success, egg or larval survival, juvenile recruitment, and population structure. The appropriate indicators differ among species, but the decision principle is consistent: conservation measures should be judged by recruitment outcomes, not only by the number of adults observed in transit.

13. FUTURE RESEARCH DIRECTIONS

Research should prioritize uncertainties that directly affect management decisions. First, multi-scale telemetry, including acoustic arrays, satellite tags, archival tags, and biological devices, should be used to identify routes, delays, mortality bottlenecks, and spawning-site use across river, estuarine, coastal, and oceanic habitats. No single tracking method covers the complete pathway; combining methods is especially important for eels, tuna, and sturgeon

(Brownscombe et al., 2019; Edwards, et al., 2024).

Second, spawning habitats should be mapped more accurately through field surveys, larval sampling, telemetry, habitat models, otolith chemistry, genetics, and environmental DNA (eDNA). eDNA can improve detection without capturing fish, but its interpretation requires caution because DNA production, transport, and degradation can complicate fine-scale inference. It is strongest when used with conventional ecological evidence rather than as a stand-alone indicator (Goldberg, et al., 2016).

Third, long-term monitoring should test how climate-driven changes in temperature, discharge, salinity, oxygen, and currents alter migration timing and recruitment. Small shifts can create mismatches between spawning, egg development, larval food availability, and nursery conditions (Ficke, et al., 2007). Genetic and genomic studies should be integrated with tracking data to identify distinct breeding populations, estimate connectivity, and avoid treating biologically different groups as one stock.

Finally, conservation actions require outcome-based evaluation. Fish passages, dam removals, seasonal closures, protected areas, and hatchery programs should be assessed through spawning success, egg survival, juvenile recruitment, and genetic diversity. Hatchery interventions may sup-port depleted populations, but poorly designed programs can create genetic risks. Shared databases and international collaboration are essential where migration routes cross administrative boundaries (Busack and Currents, 1995; Hedgecock and Coykendall, 2007).

13.CONCLUSION

Fish migration for reproduction is a coordinated ecological and physiological strategy that links adult movement with spawning-site access, egg development, larval survival, and recruitment. The principal migration patterns—anadromous, catadromous, potamodromous, oceanodromous, and amphidromous—differ in direction and habitat use, but each depends on connectivity among the habitats needed at successive life stages.

Migration timing and navigation emerge from interacting cues, including temperature, flow, rainfall, salinity, chemical signals, magnetic information, and photoperiod. Successful movement also depends on osmoregulation, stored energy, endocrine regulation, swimming endurance, and reproductive transformation. Salmon, European eels, sturgeons, and tuna illustrate how these mechanisms operate across freshwater, estuarine, and marine systems.

The strongest management implication is that protecting a spawning site alone is insufficient. Dams, altered flow, warming water, pollution, habitat loss, and fishing during spawning movements can disrupt different stages of the same reproductive pathway. Conservation should therefore com-bine route restoration, spawning-habitat protection, seasonal fishery controls, species-appropriate passage, and long-term monitoring of recruitment outcomes. Maintaining reproductive migration is essential for fish biodiversity, resilient fisheries, and the ecological functions of aquatic ecosystems.

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Chapter 6

Impact Of Workplace Redesign On Productivity: 5S Implementatıon in A Parquet Company*

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Abstract

With the advancement of technology and the increasing competition in the global market, it has become inevitable for businesses to adopt lean manufacturing techniques to improve operational efficiency. In this study, the 5S methodology, one of the core lean manufacturing techniques, was implemented in a laminated parquet manufacturing company operating within the forest products industry. The aim of the study was to reorganize the workplace through the implementation of the 5S methodology and to evaluate its positive and negative effects on operational efficiency. For this purpose, data were collected and analyzed for the periods before, during, and after the implementation of the 5S methodology. The findings revealed that the implementation of the 5S methodology resulted in a 20% improvement in labor productivity. In addition, the time required for cleaning operations was reduced from 17 minutes to 10 minutes. Furthermore, following the implementation of the 5S methodology, the average production output increased by 38.4% over the last two years.

Keywords: 5S, Productivity, Forest products industry, Duzce

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Özet

Gelişen teknoloji ve küresel pazarda işletmelerin daha verimli çalışabilmesi için yalın üretim teknikleri üzerinde çalışmalar yapması kaçınılmaz hale gelmiştir. Yapılan bu çalışmada yalın üretim tekniklerinden biri olan 5S uygulaması, orman ürünleri sanayisinin bir alt dalı olan lamine parke işletmesinde gerçekleşmiştir. Bu çalışma ile 5S tekniği uygulanarak, işletmenin yeniden düzenlenmesi sağlanarak verimliliğe olumlu ya da olumsuz sonuçlarını ortaya çıkarmak amaçlanmıştır. Çalışmada öncelikle 5S tekniği uygulamasının öncesi, uygulama dönemi ve sonrası kayıt edilerek analizler yapılmıştır. Çalışma sonucunda 5S tekniği ile %20 oranında iş gücü kazanımı elde edilmiştir. Yine çalışma sonucunda 5S tekniği uygulanması ile 17 dakika olan temizlik işleminin 10 dakikaya düşürüldüğü belirlenmiştir. Uygulama sonucu son 2 yılda ortalama ürün metrajında 5S tekniği sonucunda %38,4 oranında artış gözlenmiştir.

Anahtar Kelimeler: 5S, Verimlilik, Orman ürünleri endüstrisi, Düzce

1. INTRODUCTION

In today's dynamic and rapidly evolving technological environment, businesses must remain competitive and innovative in the products and services they offer in order to sustain their commercial activities. In this context, the adoption of the Kaizen philosophy within organizations is of critical importance. Kaizen, a management strategy based on the principle of continuous improvement, serves as a vital tool for businesses to achieve sustainable success and gain a competitive advantage. In effectively managing this process, managers need to focus on two key aspects: first, making the best choices by selecting the right decisions, and second, identifying the most effective methods to enhance organizational performance. In selecting these methods, it is crucial for managers not only to assess the quality of performance but also to promote continuous improvement processes for sustainable development.

One of the most critical factors affecting business performance is the organization and orderliness of the work environment. A well-organized workplace has a direct positive impact on employees' physical and psychological well-being, thereby increasing productivity. Furthermore, the foundation of this positive impact rests heavily on occupational health and safety (OHS) awareness within the sector, underscoring the importance of analyzing and enhancing OHS awareness starting in higher education (Çil & Gedik, 2024). In this regard, the 5S quality management philosophy is a widely adopted management technique that serves as an effective tool for organizing workspaces (Kumar & Kumar, 2012). However, for 5S practices to be successfully implemented, it is essential not only to apply them but also to ensure their sustainability. Sustainability is crucial for maintaining the long-term effectiveness of quality management techniques. In this context, managers play a significant role, and two key factors—leadership and employee engagement—must be emphasized to ensure the continuity of these practices (Sevim Korkut et al., 2009; Liyanage et al., 2010). Contemporary research in the manufacturing sector shows that safety climate factors directly influence employees' safety behaviors, underscoring the strategic role of management in establishing a sustainable safety culture (Çil, 2025). Effectively managing these factors will help establish 5S practices as a lasting culture within the organization.

The 5S philosophy aims to manage a workplace through a sequence of specific techniques, with each step building upon the previous one. These techniques—sorting, setting in order, shining, standardizing, and sustaining—are designed to create a clean, ergonomic, and safe working environment for all stakeholders (Gupta, 2022).

The significance of 5S, as discussed in the literature (Burton and Boeder, 2003; Liker, 2004; Liker and Meier, 2005; Black and Miller, 2008), is outlined through the following five key steps:

• *Sort (Seiri)* – The process of distinguishing and removing unnecessary items, keeping only the essential tools and materials in the workspace;

• *Straighten (Seiton)* – Arranging frequently used items in a logical and organized manner, ensuring that each item is stored in a designated location;

• *Shine (Seiso)* – Conducting thorough cleaning and maintaining cleanliness by eliminating dirt sources, simplifying the cleaning process, as quality can only be achieved in a clean working environment;

• *Standardize (Seiketsu)* – Establishing clear visual rules and storage guidelines, along with training to maintain these standards, aiming to reduce time spent searching for items and minimizing the potential for mistakes;

• *Sustain (Shitsuke)* – Continuously monitoring, evaluating, and improving all activities to ensure that the results achieved through the 5S implementation are sustained over time.

This philosophy not only aims to establish organization but also enhances productivity and safety in the workplace. The *Sustain* step plays a crucial role in ensuring the continuity and long-term effectiveness of the 5S methodology.

2. MATERIALS and METHODS

The 5S methodology is an acronym derived from five fundamental principles of Japanese origin: Seiri (Sort), Seiton (Straighten), Seiso (Shine), Seiketsu (Standardize), and Shitsuke (Sustain). Based on these principles, the 5S method is a lean production management technique used to systematically identify and eliminate waste. While 5S is commonly associated with defining a tidy and organized workplace, its primary focus is on ensuring the sustainability of such an environment (Niemann et al., 2024). In this study, a 5S implementation was carried out in a company engaged in the production of engineered wood flooring as an alternative to solid parquet. The company was established in 2007 in Düzce, Turkey. At the time of the study, the company employed a total of 125 personnel, including 8 engineers, 3 technicians, 2 administrative staff, and 112 blue-collar workers. The facility covers a total area of 72,686 square meters, comprising 62,295 m^2 of open space and 10,391 m^2 of enclosed space. Serving both domestic and international markets, the company manufactures two-layer and three-layer engineered wood flooring. The annual production capacity of engineered flooring is determined to be 588,545 square meters.

This study highlights several key factors that demonstrate the necessity of implementing the 5S methodology within the organization. As the company's production capacity and workforce expanded rapidly, the existing production areas became increasingly inadequate to accommodate this growth, resulting in significant operational challenges. The current production system was characterized by considerable time losses associated with searching for materials and products, while the disorganized arrangement of semi-finished products made it difficult to distinguish between scrap materials, usable products, and components requiring reprocessing. These inefficiencies hindered employees from performing their duties and responsibilities effectively. Furthermore, the continuous advancement of the wood products industry and the increasing demand for higher quality standards have further emphasized the importance of employee training and competency development. Within this context, the implementation of the 5S methodology was intended to eliminate unnecessary time losses and operational waste, improve organizational performance, eliminate workplace disorder, enhance employee competence, increase process transparency, and establish standardized operating procedures. Ultimately, these improvements were expected to create a more flexible, efficient, and sustainable production system.

The study was conducted in the grading (sorting) department of an engineered wood flooring manufacturing company. The grading process involves classifying veneer lamellas into predefined quality categories after the timber has been four-side planed and subsequently sliced into thin lamellas. The classification is performed according to the physical characteristics of the material, primarily including color consistency, knot characteristics, and the presence of surface cracks or other visual defects.

The 5S implementation was carried out systematically through a structured sequence of stages. Prior to implementation, meetings were organized with managers and production supervisors to establish the implementation strategy. The production area was divided into several zones, and the department requiring the highest level of improvement was identified. Based on this preliminary assessment, the grading department was selected as the pilot implementation area, and dedicated teams were established to manage the process. These teams subsequently implemented each stage of the 5S methodology in sequence.

During the “Sort (Seiri)” and “Set in Order (Seiton)” stages, all existing equipment, tools, and materials were comprehensively evaluated, and a utilization-frequency analysis was conducted to determine operational requirements. Based on this assessment, a material allocation schedule was developed. In the Set in Order stage, designated storage locations were established according to operational necessity, and the stacking arrangement of pallets containing veneer lamellas was reorganized to improve material flow.

Furthermore, a visual labeling system was introduced to enhance workplace organization, facilitate process traceability, and minimize operational confusion. As a result of these improvements, the previously fragmented and non-linear production layout was transformed into a streamlined linear production flow, thereby improving workflow efficiency.

During the “Shine (Seiso)” stage, comprehensive cleaning procedures were established by specifying which production areas would be cleaned, the responsible personnel, the required cleaning frequency, and the estimated duration of each cleaning activity. Detailed written cleaning instructions, including the equipment to be used and the tasks to be performed, were distributed to the supervisors responsible for each production area.

During the “Standardize (Seiketsu)” stage, routine inspections conducted by shift supervisors were introduced to ensure the long-term sustainability of the improvements achieved during the previous stages. Finally, during the “Sustain (Shitsuke)” stage, continuous training programs were organized to strengthen employees' awareness of the 5S philosophy and encourage the adoption of standardized work practices as part of the organizational culture. In this regard, regular training sessions conducted by management played a critical role in maintaining employee commitment and ensuring the long-term sustainability of the 5S implementation.

3. RESULTS

The study was conducted in the veneer lamella grading department of the engineered wood flooring production line. To evaluate the effectiveness of the 5S implementation, one year of production data was collected and recorded prior to the implementation. The implementation process, the anticipated operational improvements, and the integration of the 5S philosophy into the organizational culture were continuously monitored through employee training programs and regular supervisory audits (Omogbai & Salonitis, 2017; Leming-Lee et al., 2019). Accordingly, all employees involved in the study received comprehensive training before the sequential implementation of the five stages of the 5S methodology. The production performance obtained during the implementation period was subsequently compared with both the pre-implementation and post-implementation datasets to evaluate the effectiveness of the system.

The production workflow of the veneer lamella grading department, where the 5S methodology was implemented, was comprehensively examined. In the engineered wood flooring manufacturing process, rough timber strips are first transferred to the drying kiln and subsequently processed through a four-side planer. Following the planing operation, the workpieces are fed into a slicing machine, where they are converted into thin veneer lamellas. These lamellas are then subjected to a pressing process to produce the surface layer of the engineered flooring. After pressing, the flooring panels undergo sanding before being transferred to the finishing line for varnishing. Once the finishing process has been completed, the panels are conveyed to the profiling machine, where the tongue-and-groove joints are machined, after which the finished products are transferred to the packaging department.

Within the grading department, the planed veneer lamellas are sorted into predefined quality classes according to established grading criteria. A total of five employees are assigned to this department. Four operators are responsible for grading the veneer lamellas in accordance with the quality specifications established by the Turkish Standards Institution (TSE), while one employee performs material handling activities by transporting and replacing the selected veneer bundles between workstations, thereby ensuring the continuity of the grading process.

Step 1. Sort (Seiri): The first stage of the 5S methodology, “Sort (Seiri)”, focuses on systematically identifying, classifying, and organizing all equipment, tools, and materials within the workplace to improve operational efficiency (Khanna, 2009). The primary objective of this stage is to distinguish essential items from unnecessary ones and eliminate all non-value-adding materials from the work environment. Accordingly, all equipment and workplace materials were evaluated based on their frequency of use and operational necessity. Following this assessment, a comprehensive material classification schedule was established, and the sorting process was implemented according to the criteria presented in “Table 1”.

Table 1. Material Classification Schedule Used During the Sort (Seiri) Stage of the 5S Implementation

Tools and Equipment	Very Frequently	Frequently	Rarely	Unnecessary	Must Not Be Present
Pallet		x			
Scissor Lift Pallet Truck	x				
Chalk	x				
Production Form		x			
Broom and Dustpan		x			
Scrap Paperboard				x	
Work-in-Progress (WIP) Paperboard			x		
Paper Clips and Pins			x		
Sticky Notes		x			
Electric Pallet Truck			x		
Marker	x				
Label		x			
Hand Tool Box					x
Utility Knives					x

To prevent newly sliced veneer lamellas awaiting grading from being mixed with those that had already been classified, each pallet was clearly labeled according to its processing status and positioned in designated storage locations. This visual management system significantly improved material traceability and minimized the risk of handling errors throughout the production process.

Previously disorganized veneer lamella pallets were systematically reorganized and classified. Materials identified as scrap or defective were labeled accordingly and removed from the active production area to eliminate unnecessary congestion and improve workplace organization. Furthermore, all equipment and workplace tools were reviewed based on the material classification schedule developed during the "Sort (Seiri)" stage and subsequently rearranged according to the established operational criteria.

Within the production system, the grading department functions as the immediate downstream customer of the four-side planing process while simultaneously serving as the upstream supplier for the surface-layer pressing operation. An analysis of the existing production layout revealed that the positioning of auxiliary equipment was inefficient and negatively affected material flow. Consequently, the workplace layout was redesigned to optimize production efficiency by establishing a continuous linear workflow that minimized unnecessary transportation and handling activities. The production layouts before and after the 5S implementation are presented in "Figure 2".

Figure 1. Comparison of veneer lamella pallet organization before and after the 5S implementation, together with the visual identification cards introduced as part of the 5S system.

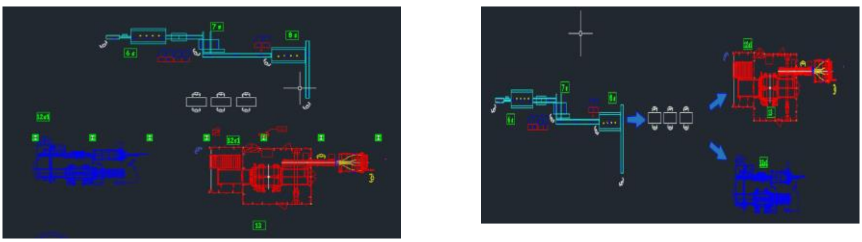

Figure 2. Production layout before and after the implementation of the 5S methodology.

Step 3. Shine (Seiso): The “Shine (Seiso)” stage of the 5S methodology is particularly critical in the wood products industry. Effective housekeeping plays a vital role in preventing equipment failures caused by wood dust accumulation, preserving the surface quality of varnished engineered wood flooring, and protecting employee health by minimizing occupational exposure to airborne dust particles. Furthermore, considering the combustible nature of wood-based materials, rigorous cleaning procedures are essential for reducing fire hazards and maintaining a safe production environment.

To support these objectives, two employees were assigned responsibility for maintaining the cleanliness of the entire engineered wood flooring production facility. However, it was recognized that sustainable workplace cleanliness could not be achieved solely through dedicated cleaning personnel. Therefore, cross-departmental collaboration was encouraged, with each production team assuming responsibility for maintaining the cleanliness of its own work area at predetermined intervals. Cleaning schedules were established by considering the operational workload of each machine and the size of the respective production area. Consequently, routine cleaning activities were incorporated into the production schedule and performed during the designated period before the end of each working shift.

Specific cleaning procedures were developed for the grading department, and detailed instructions describing the required cleaning tasks were communicated to the responsible employees. Sawdust, wood dust, and production residues generated during the grading process were removed using appropriate cleaning equipment, including brushes and compressed air systems. During all cleaning operations, employees were required to wear appropriate personal protective equipment (PPE), including dust masks and protective gloves. In addition, undersized wood components generated during grading were collected in designated sacks and removed from the production area, while empty pallets were systematically organized and stored in assigned storage locations.

These improvements enhanced not only the overall appearance and organization of the workplace but also the accessibility of tools and materials. As a result, operational abnormalities and potential process-related problems became more visible, facilitating earlier identification and more effective corrective actions through improved visual management.

Step 4. Standardize (Seiketsu): The “Standardize (Seiketsu” stage focuses on transforming the improvements achieved during the “Sort (Seiri)”, “Set in Order (Seiton)”, and “Shine (Seiso)” stages into standardized operating procedures to ensure their long-term sustainability. Throughout the study, the outcomes of the implemented improvements were comprehensively communicated to all employees. It was emphasized that these practices had become part of the company's standard operating procedures and that responsibility for maintaining them was shared across all organizational levels.

During the standardization process, previously implemented practices were continuously monitored, and identified deficiencies were systematically addressed through continuous improvement activities. Responsibility for supervising employee compliance with the established standards was assigned to shift supervisors, who conducted regular workplace inspections to ensure process consistency. These periodic audits played a crucial role in preserving the implemented improvements and integrating standardized practices into routine production activities.

Step 5. Sustain (Shitsuke): The final stage of the 5S methodology, “Sustain (Shitsuke)”, aims to embed the implemented improvements and standardized procedures into the organizational culture, thereby ensuring their long-term continuity. To achieve this objective, comprehensive training programs were organized to familiarize employees with the newly established procedures and workplace standards. These training activities were designed not only to introduce new working methods but also to promote their adoption as routine workplace practices.

Throughout this stage, company management continuously monitored the implementation process and carried out activities to strengthen employees' sense of responsibility toward maintaining standardized practices. Regular inspections conducted by shift supervisors ensured ongoing compliance with established procedures, allowing the improvements achieved through the 5S implementation to become institutionalized as an integral component of the organization's operational culture.

Production Performance Evaluation: The improvements achieved following the implementation of the 5S methodology in the grading department were evaluated by comparing production records collected before, during, and after the implementation period. The statistical analysis incorporated production data from the 12-month pre-implementation period, the implementation period, and the 12-month post-implementation period.

The evaluated performance indicators included the total graded production area (m^2), average daily production (m^2), average daily workforce, and average daily production per employee (m^2). These indicators enabled a quantitative comparison of operational performance before and after the implementation of the 5S methodology. The differences observed between the two periods were subsequently used to assess the contribution of the 5S implementation to overall production efficiency (Table 2).

To obtain an accurate estimate of the average workforce, fluctuations in the number of employees throughout daily working hours were taken into account. Accordingly, employee attendance was first calculated on an hourly basis and subsequently converted into the average number of workers assigned per day. This approach provided a more reliable representation of workforce utilization and allowed variations in labor allocation throughout the production process to be incorporated into the productivity analysis.

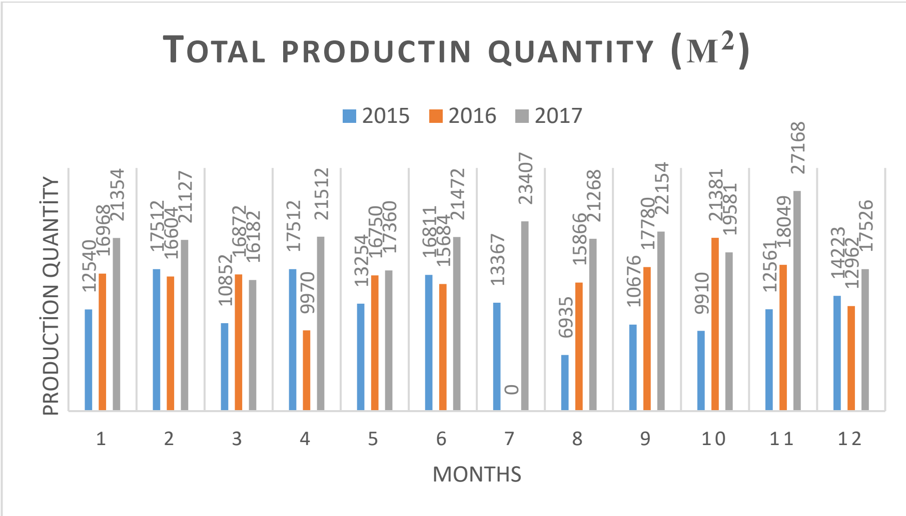

Figure 3. Production performance indicators before, during, and after the implementation of the 5S methodology (No data recorded for July 2016).

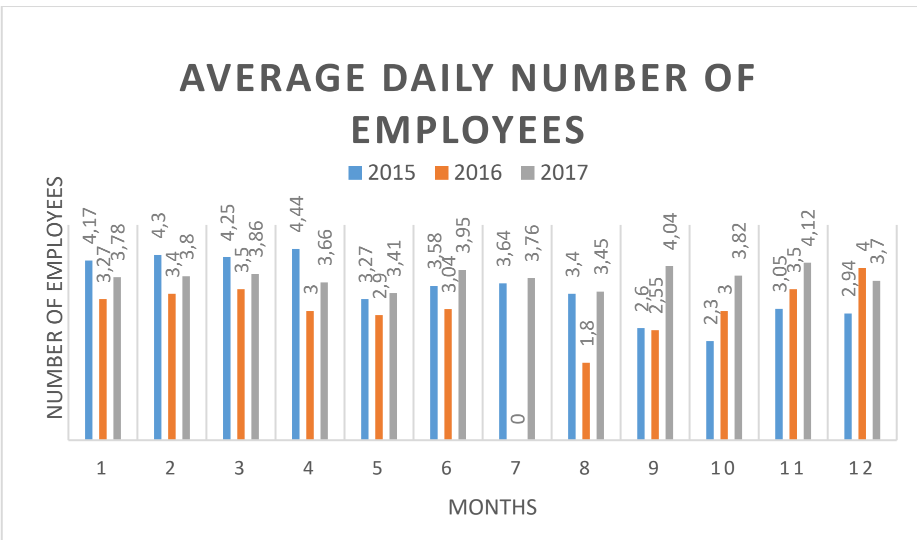

Figure 4. Production performance indicators before, during, and after the implementation of the 5S methodology (No data recorded for July 2016).

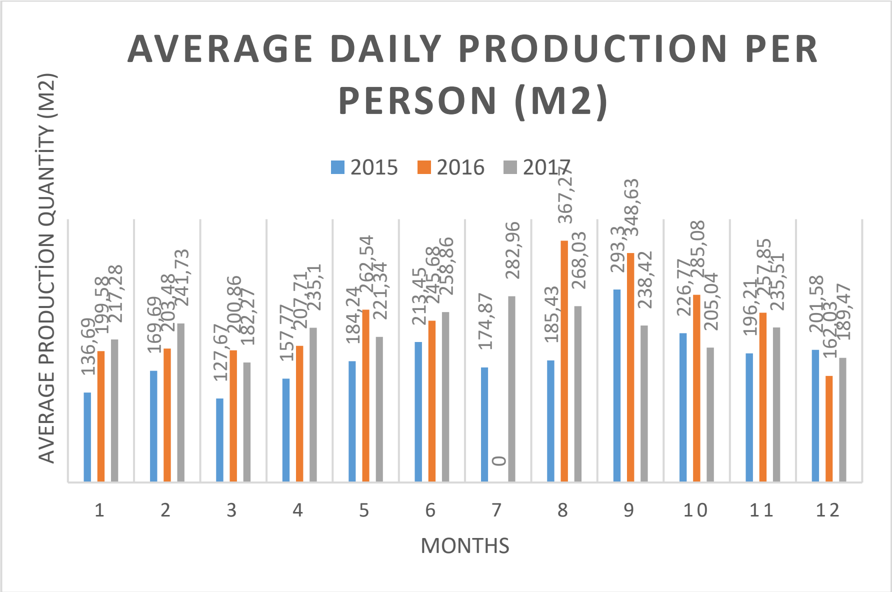

Figure 5. Production performance indicators before, during, and after the implementation of the 5S methodology (No data recorded for July 2016).

Pre-implementation Period (2015). The production data collected during the 12-month period prior to the implementation of the 5S methodology indicate that a total of 156.153 m² of veneer lamellas were graded. Based on the factory's effective production time, the grading department achieved an average daily production volume of 637.63 m². During this period, the grading process was carried out by an average workforce of 3.50 employees per day, resulting in an average daily productivity of 188.97 m² per employee.

Implementation Period (2016). An analysis of the production records collected during the implementation phase revealed that production data for July 2016 were unavailable. Consequently, all performance calculations were based on the remaining 11 months of recorded production. During this period, a total of 178,886 m² of veneer lamellas were graded, corresponding to an average daily production volume of 677.89 m². The average daily workforce decreased to 2.83 employees, while average labor productivity increased to 228.39 m² per employee per day.

Post-implementation Period (2017). Following the full implementation of the 5S methodology, production performance improved substantially. During the 12-month post-implementation period, the grading department processed a total of 250,111 m² of veneer lamellas. Considering the effective production time of the facility, the average daily production increased to 873.97 m². The average workforce during this period was 3.78 employees per day, and average daily productivity reached 231.33 m² per employee.

The comparative analysis of the production records demonstrates that the implementation of the 5S methodology resulted in substantial improvements in operational performance within the grading department. Compared with the pre-implementation period, the following improvements were observed:

A 60.2% increase in annual production volume;

A 37.1% increase in average daily production;

A 22.4% increase in average daily productivity per employee.

These findings demonstrate that the 5S methodology is an effective management tool for improving manufacturing performance. In particular, the optimization of workforce utilization contributed significantly to increasing daily production capacity while simultaneously enhancing labor productivity. Overall, the results indicate that the implementation of the 5S methodology enabled more efficient utilization of organizational resources and substantially improved the operational performance of the grading process.

Comparison with Previous Studies

Previous studies have consistently demonstrated that the 5S methodology is an effective productivity improvement tool across both manufacturing and service industries. Beyond improving workplace organization, 5S has also been reported to facilitate organizational development and enhance operational efficiency regardless of the industrial sector in which it is implemented (Deros et al., 2012; Ertaş, 2017; Çavmak, 2018; Sremcev et al., 2018; Yağlı et al., 2024).

Sector-specific studies further support the findings of the present research. Roriz et al. (2017) reported that implementing the 5S methodology in a carton manufacturing facility reduced setup time by 47%, highlighting its effectiveness in improving production efficiency. Similarly, Karşıyaka and Sütçü (2019) demonstrated that integrating 5S with other lean manufacturing techniques in the upholstery department of a furniture manufacturing company increased workstation efficiency, reduced quality losses in intermediate inventory areas, and resulted in an overall 38% improvement in productivity.

Likewise, Kara (2024) reported an 8.56% improvement in Overall Equipment Effectiveness (OEE) following the implementation of the 5S methodology to eliminate production bottlenecks and operational waste in a machining facility. In another study conducted in the carton and packaging industry, Ünal et al. (2024) concluded that 5S implementation created a cleaner, more organized, and ergonomically improved workplace, which ultimately contributed to enhanced overall production performance.

Collectively, these studies confirm that the 5S methodology is a highly effective lean manufacturing tool for improving workplace organization, operational efficiency, product quality, and overall manufacturing performance. The findings of the present study are consistent with the existing literature, demonstrating that systematic implementation of the 5S methodology can generate substantial productivity gains within engineered wood flooring manufacturing.

More recently, Horasan (2025) reported that implementing the 5S methodology in a veneer manufacturing facility resulted in a 36.79% reduction in cabinet assembly time and a 59.40% increase in daily cabinet production, further supporting the effectiveness of 5S in improving operational performance across different sectors of the wood products industry.

4. CONCLUSIONS

During the initial months of the 5S implementation, the grading department experienced difficulties in achieving the targeted production output due to employees' adaptation to the newly introduced work procedures. As personnel gradually became familiar with the 5S methodology and the planned workplace improvements were fully implemented, production performance improved steadily, and measurable operational benefits were observed within a relatively short period.

At the end of the three-year implementation period, the accumulated performance data indicated that one position within the grading department had become redundant. Consequently, the workforce in this department was reduced by one employee without adversely affecting production performance, demonstrating that the 5S methodology contributed not only to productivity improvement but also to labor optimization. Continuous improvements were observed throughout each phase of the implementation. In particular, following the “Shine (Seiso)” stage, the average time required for routine cleaning activities decreased from approximately “17 minutes to 10 minutes”, corresponding to an estimated “41% reduction in cleaning time”. This improvement increased the time available for value-added production activities while simultaneously enhancing workplace safety and operational efficiency.

Regardless of their size, manufacturing enterprises operating in highly competitive markets should continuously seek to eliminate all forms of operational waste. One of the primary objectives of the present study was to reduce non-value-added activities and unnecessary time losses through the systematic implementation of the 5S methodology. The operational improvements achieved throughout the study clearly demonstrate that this objective was successfully accomplished.

The findings further indicate that the stepwise implementation of the 5S methodology significantly enhanced production performance within the grading department. Compared with the baseline conditions, average daily production per employee increased by 22.4%, while total annual production increased by 60.2%. These results confirm that systematic workplace organization, standardized operating procedures, and continuous improvement practices can substantially enhance manufacturing efficiency.

Overall, this study provides empirical evidence of the positive impact of the 5S methodology on both operational productivity and organizational profitability in engineered wood flooring manufacturing. Although the present implementation was limited to the grading department, the results suggest that extending the 5S methodology to other production departments could generate even greater improvements in manufacturing performance and operational efficiency. Furthermore, the positive attitudes demonstrated by employees toward the implemented practices indicate that workforce engagement represents a critical success factor for ensuring the long-term sustainability of continuous improvement initiatives within manufacturing organizations.

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