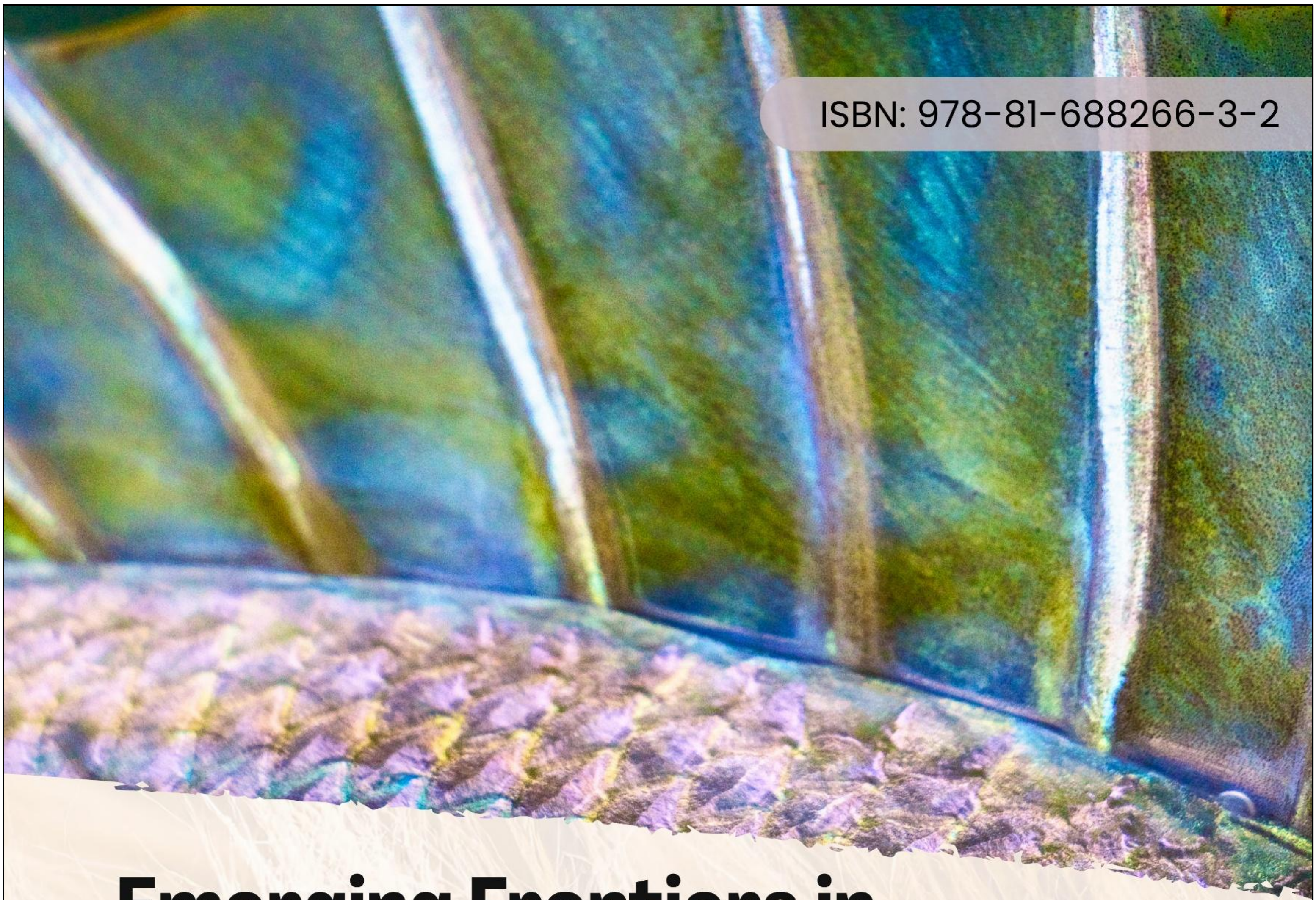

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Emerging Frontiers in Animal Science and Biotechnology

Editors:
Prof. (Dr.) Vinay Dwivedi
Dr. Divya Gupta
Dr. Sadhana Shrivastava

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PREFACE

Animal science and biotechnology have entered an exciting era of innovation, driven by advances in molecular biology, genetics, genomics, reproductive technologies, bioinformatics, artificial intelligence, and sustainable production systems. These developments are transforming our understanding of animal health, nutrition, breeding, welfare, biodiversity conservation, and livestock productivity while addressing global challenges related to food security, environmental sustainability, climate resilience, and emerging diseases. *Emerging Frontiers in Animal Science and Biotechnology* brings together scholarly contributions that highlight the latest research, technological innovations, and interdisciplinary perspectives shaping the future of these rapidly evolving disciplines.

This volume features chapters contributed by distinguished researchers, academicians, and professionals covering diverse areas including animal physiology, genetics, genomics, microbiology, immunology, reproductive biotechnology, aquaculture, veterinary sciences, animal nutrition, biotechnology, wildlife conservation, bioinformatics, precision livestock farming, and sustainable animal production. The chapters combine fundamental scientific principles with contemporary research and practical applications, illustrating how innovative approaches can improve productivity, animal welfare, disease management, and conservation efforts. By integrating laboratory discoveries with field-based practices, this book emphasizes the importance of translating scientific knowledge into practical solutions that benefit researchers, educators, students, veterinarians, farmers, policymakers, and industry stakeholders while promoting responsible resource management and sustainable development.

The objective of this book is to provide readers with a comprehensive and reliable reference that bridges foundational concepts with emerging technologies and current scientific advancements. It also seeks to encourage interdisciplinary collaboration among scientists, educators, industry experts, and policymakers to foster innovation and accelerate scientific progress.

The editors sincerely express their gratitude to all contributing authors, reviewers, and the publishing team for their valuable efforts and unwavering support. We hope this volume will inspire future research, strengthen academic excellence, encourage technological innovation, and contribute significantly to the continued advancement of animal science and biotechnology for the benefit of society and future generations.

- Editors

TABLE OF CONTENT

FROM POLLUTION TO SOLUTION: MICROBIAL AND ENZYMATIC APPROACHES TO PLASTIC WASTE BIOREMEDIATION

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Abstract

The widespread use of plastic materials has significantly improved modern living standards; however, their excessive production and improper disposal have created a serious environmental burden worldwide. Due to their chemically stable structure and slow natural degradation, plastic wastes continue to accumulate in land, freshwater, and marine ecosystems, where they gradually break down into microplastics and nanoplastics. These smaller particles are increasingly recognized as emerging pollutants because of their persistence, mobility, and ability to interact with toxic chemicals and biological contaminants. Managing plastic waste through conventional means — whether by burying it in landfills, incinerating it, or mechanically recycling it — has proven problematic, as each approach carries its own set of technical, economic, and environmental challenges. In recent years, microbial bioremediation has gained scientific attention as a sustainable alternative for plastic waste treatment. Various microorganisms, including bacteria, fungi, algae, and mixed microbial communities, have demonstrated the ability to colonize plastic surfaces and initiate polymer degradation through enzymatic mechanisms. Enzymes such as PETase, cutinase, laccase, and esterase play an important role in transforming complex polymer chains into simpler biodegradable compounds. Recent developments in molecular biology, metagenomics, enzyme engineering, and synthetic biology have further improved the understanding and efficiency of microbial plastic degradation systems. This chapter discusses the environmental consequences of plastic and microplastic pollution, the microbial mechanisms involved in polymer degradation, major plastic-degrading microorganisms, recent technological advancements, and future opportunities for large-scale environmental applications.

Keywords: Plastic Pollution, Microplastics, Microbial Bioremediation, Plastic-Degrading Microorganisms, Enzymatic Degradation, Sustainable Waste Management.

Introduction

The rapid expansion of industrial development, urbanization, and consumer-driven lifestyles has led to an unprecedented increase in the production and use of plastic materials across the globe. Since their large-scale introduction during the twentieth century, plastics have become essential in sectors such as packaging, healthcare, agriculture, electronics, construction, and transportation because of their durability, flexibility, lightweight nature, and cost-effectiveness. Although these properties have made plastics highly valuable in modern society, their long-term persistence in the environment has created a major ecological challenge. Large quantities of plastic waste are generated every year, and a significant proportion enters natural ecosystems because of inefficient waste management practices, uncontrolled disposal, and limited recycling infrastructure (Geyer *et al.,* 2017). Once released into the environment, plastic materials undergo gradual physical, chemical, and biological weathering, leading to the formation of smaller fragments known as microplastics and nanoplastics. These particles have been detected in oceans, rivers, agricultural soils, atmospheric particles, food products, and even biological tissues, highlighting their widespread environmental distribution. Their ability to adsorb hazardous pollutants, transport microbial pathogens, and enter food chains has raised concerns regarding ecosystem health and potential human exposure (Jambeck *et al.,* 2015; Wright and Kelly, 2017). Conventional waste treatment approaches such as landfilling, open burning, incineration, and mechanical recycling have not been sufficient to control the growing plastic crisis. In many cases, these methods may generate secondary pollutants, greenhouse gas emissions, or reduced-quality recycled materials. As a result, there is an increasing demand for environmentally sustainable alternatives capable of reducing plastic accumulation more efficiently. Among emerging solutions, microbial bioremediation has attracted considerable scientific interest. Naturally occurring microorganisms, including bacteria, fungi, and algae, possess the ability to interact with plastic surfaces, form biofilms, and secrete extracellular enzymes capable of modifying and degrading polymer structures. The discovery of *Ideonella sakaiensis* and its PET-degrading enzyme system has significantly advanced this field and demonstrated the biological potential for synthetic polymer degradation. In addition, recent advances in metagenomics, proteomics, and synthetic biology are helping researchers identify novel microbial strains and engineer more efficient enzyme systems for environmental applications.

Literature Review

The growing use of plastic materials over the last several decades has created serious environmental concerns across the world. Since synthetic plastics became commercially available in the mid-twentieth century, their application has expanded rapidly in packaging, medicine, agriculture, transportation, and household products because of their strength, flexibility, low weight, and economic value. Despite these advantages, the continuous increase in plastic consumption, combined with ineffective waste handling systems, has resulted in the long-term accumulation of plastic debris in both terrestrial and aquatic ecosystems. Global assessments indicate that only a limited proportion of discarded plastic is successfully recycled, whereas a large quantity remains in landfills or enters natural habitats, where it can persist for many years **(**Geyer *et al*.**,**2017**)**. As plastic materials remain exposed to environmental conditions, they gradually fragment into smaller particles known as microplastics. These particles, usually measuring less than 5 mm, are produced through prolonged exposure to sunlight, temperature fluctuations, oxidation reactions, and physical erosion. Because of their small size and widespread mobility, microplastics have now been identified in marine environments, freshwater systems, agricultural land, atmospheric dust, and even food-related samples. Their ability to interact with toxic compounds, metallic contaminants, and disease-causing microorganisms has raised important concerns regarding ecological stability and possible risks to human health **(**Jambeck *et al.,* 2015; Wright and Kelly, 2017). For many years, synthetic polymers were considered biologically inert because their compact molecular arrangement, hydrophobic nature, and chemically stable backbone structure made microbial attack extremely difficult. However, recent investigations have shown that natural microbial populations can attach to plastic surfaces and establish organized biofilm communities. This microbial colonization has led to the recognition of the "plastisphere," a specialized ecological microenvironment formed on plastic debris in aquatic systems. Inhabiting this plastic-bound microworld, these microorganisms undergo metabolic adjustments and produce extracellular enzymes capable of chemically altering the polymer surface, initiating what becomes a slow but progressive process of material breakdown (Zettler *et al.,* 2013). The susceptibility of plastics to biodegradation differs according to polymer composition. Polyester-based plastics such as PET are generally more vulnerable to microbial degradation because ester linkages present in their structure are more accessible to enzymatic hydrolysis. In contrast, polymers such as PE, PP, and PS possess stronger carbon–carbon bonds, which make biological degradation slower and more difficult (Tokiwa *et al.,* 2009). Even so, several microbial groups including *Pseudomonas*, *Bacillus*, and *Rhodococcus* have demonstrated measurable degradation activity under controlled laboratory conditions **(**Restrepo-Flórez *et.al*.**,** 2014; Wilkes and Aristilde, 2017). Modern molecular techniques have significantly expanded current knowledge of microbial plastic degradation. Approaches such as metagenomic analysis, proteomic profiling, and synthetic biology have enabled researchers to identify previously unknown degradation genes, metabolic pathways, and enzyme systems involved in polymer breakdown **(**Danso *et al.,* 2018**).** Furthermore, advances in enzyme engineering have improved the catalytic efficiency, substrate specificity, and thermal stability of plastic-degrading enzymes, increasing their relevance for industrial applications **(**Wei and Zimmermann, 2017**).** Although considerable scientific progress has been achieved, translating laboratory findings into real environmental applications remains challenging. Factors such as temperature variation, pH, oxygen concentration, polymer crystallinity, and surface morphology strongly influence microbial degradation efficiency. Therefore, future success in this field will depend on the development of robust microbial strains, improved bioprocess technologies, and economically feasible large-scale production systems **(**Urbanek *et al.,* 2018).

Types of Plastics and Their Environmental Impact

Classification of Plastics

Plastics are not a single material but a broad family of synthetic polymers, each with distinct chemical compositions, physical properties, and environmental behaviors. Understanding this diversity is essential for appreciating why plastic pollution is such a complex problem — and why no single biological solution will address all of it.

Plastics are broadly classified into two categories based on their thermal behavior. Thermoplastics can be repeatedly melted and reshaped when heated, making them amenable to mechanical recycling in theory. This group includes some of the most widely produced materials in the world: polyethylene terephthalate (PET), used in beverage bottles and synthetic textiles; high-density polyethylene (HDPE) and low-density polyethylene (LDPE), found in packaging films and containers; polypropylene (PP), used in food packaging, automotive parts, and medical equipment; polystyrene (PS), used in disposable cutlery and insulation foam; and polyvinyl chloride (PVC), used in pipes, flooring, and cable insulation. Thermosets, by contrast, undergo irreversible chemical changes during manufacturing, forming cross-linked networks that cannot be re-melted. Epoxy resins, polyurethane (PU) foam, and phenol-formaldehyde resins fall into this category. Their cross-linked structure makes them particularly resistant to both mechanical and biological degradation (Andrady, 2011; Thompson *et al.,* 2009).

A further distinction is made between conventional petroleum-based plastics and bioplastics. Bioplastics such as polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and polybutylene succinate (PBS) are derived from renewable biological sources and are generally more susceptible to microbial degradation, though even these materials degrade slowly under ambient environmental conditions (Rujnić-Sokele and Pilipović, 2017).

Table 1: Classification of Common Plastic Types

Plastic Type	**Abbreviation**	**Applications**	**Relative Biodegradability**
Polyethylene terephthalate	PET	Bottles, textiles	Moderate (with specific enzymes)
High-density polyethylene	HDPE	Containers, pipes	Low
Low-density polyethylene	LDPE	Films, bags	Very low
Polypropylene	PP	Packaging, automotive	Very low
Polystyrene	PS	Foam, cutlery	Very low
Polyvinyl chloride	PVC	Pipes, cables	Very low
Polyurethane	PU	Foam, coatings	Low–moderate
Polylactic acid	PLA	Food packaging, biomedical	Moderate–high
Polyhydroxyalkanoates	PHA	Packaging, biomedical	High

Sources of Plastic Pollution

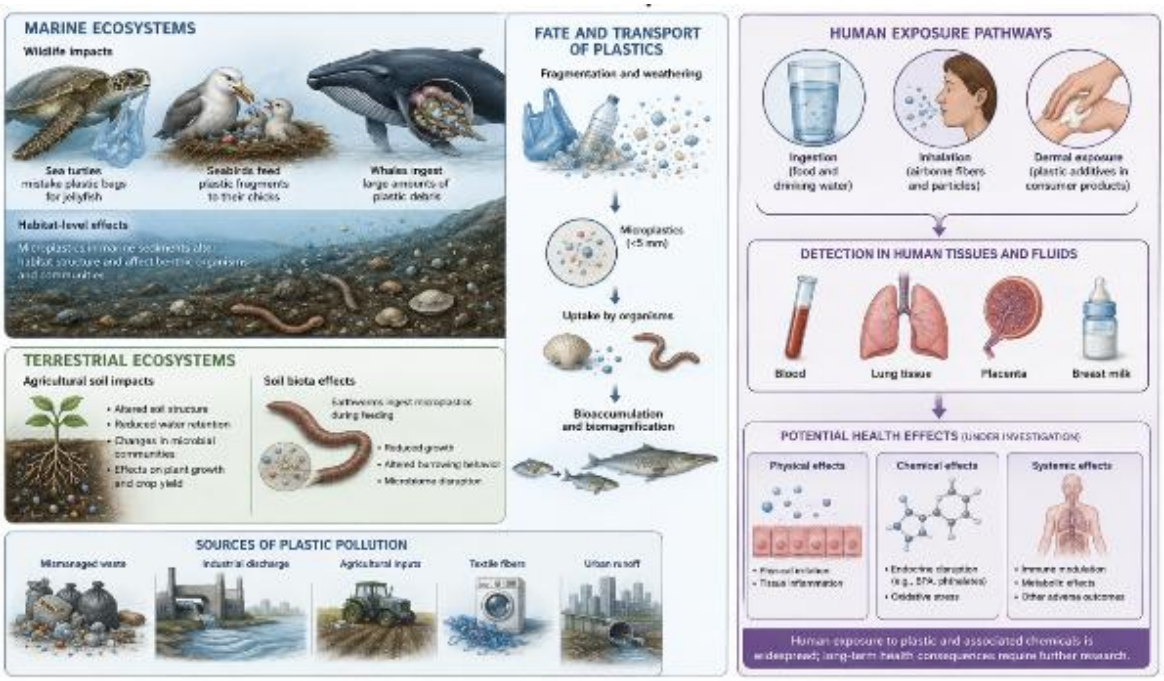
The pathways through which plastic enters the natural environment are numerous, interconnected, and largely driven by systemic failures in waste management. Globally, plastic production has grown from approximately 2 million tonnes per year in 1950 to over 400 million tonnes annually by the 2020s, and a substantial fraction of this material ultimately reaches the environment (Geyer *et al.,* 2017).

Municipal solid waste is one of the primary sources, particularly in regions where waste collection and disposal infrastructure is inadequate. As the leading application category for plastic materials, packaging is characterized by an exceptionally short use cycle — items are discarded soon after serving their purpose, and a substantial fraction of this waste reaches collection and processing systems that are ill-equipped to manage it effectively. Open dumping and burning remain common practices in many parts of the world, and both contribute to environmental plastic contamination.

Industrial and agricultural sources add considerably to the problem. Plastic mulch films, used widely in modern agriculture to regulate soil temperature and suppress weeds, fragment into microplastics over time and accumulate in agricultural soils. Industrial pellets known as "nurdles" — the raw material from which plastic products are manufactured — are frequently spilled during transport and processing, entering waterways and coastal environments. Textile washing releases synthetic microfibers from polyester and nylon garments directly into wastewater; estimates suggest that a single laundry cycle can release hundreds of thousands of microfibers that conventional wastewater treatment plants fail to fully capture (Browne *et al.,* 2011). Marine environments receive plastic from both land-based and ocean-based sources. Rivers act as major transport vectors, carrying plastic from inland disposal sites to coastal and oceanic zones. Fishing gear — nets, lines, and floats — constitutes a significant proportion of large plastic items in the ocean, particularly in areas of intensive fishing activity.

Effects on Ecosystems and Human Health

The environmental consequences of plastic accumulation extend across all major ecosystem types and affect organisms at every level of biological organization. In marine environments, the most visible effects are the entanglement and ingestion of plastics by wildlife. Sea turtles mistake floating plastic bags for jellyfish; seabirds feed plastic fragments to their chicks; large whales wash ashore with stomachs packed with plastic debris. Beyond these acute effects, the subtler chemical and physical impacts of plastic contamination are pervasive. Microplastics in marine sediments alter the physical structure of the habitat, affecting burrowing organisms and benthic communities. Plastic particles adsorb persistent organic pollutants and heavy metals from the surrounding water, concentrating these toxicants and potentially transferring them to organisms that ingest the particles (Rochman *et al.,* 2013).



Fugure 1: Effect of plastic pollution on ecosyatem and human health

Terrestrial ecosystems are equally affected, though they receive less research attention than marine environments. Microplastics in agricultural soils have been shown to affect soil structure, water retention, microbial community composition, and the growth of crop plants. Earthworms, which play a fundamental role in soil health, ingest microplastics during normal feeding activity;

studies have documented reduced growth, altered burrowing behavior, and microbiome disruption in exposed individuals (Rillig *et al.,* 2017). Human exposure to plastic-derived chemicals occurs through multiple routes: ingestion of plastic particles in food and drinking water, inhalation of airborne microplastic fibers, and dermal exposure to plastic additives in consumer products. Microplastics have now been detected in human blood, lung tissue, placenta, and breast milk, confirming that human exposure is widespread (Leslie *et al.,* 2022). The health implications of this exposure are still being investigated, but concerns have been raised about physical irritation, inflammatory responses, and the potential endocrine-disrupting effects of chemical additives such as bisphenol A (BPA) and phthalates that leach from plastic materials.

Microorganisms Involved in Plastic Degradation

1. Bacteria

Bacteria represent the most extensively studied group of plastic-degrading microorganisms, owing to their metabolic diversity, rapid growth rates, and ease of cultivation in laboratory settings. Their activity against plastic surfaces has been documented across a wide range of polymer types and environmental contexts.

Ideonella sakaiensis 201-F6 is arguably the most celebrated bacterial discovery in this field. (Yoshida *et al.,* 2016) isolated this organism from a PET bottle recycling site in Sakai, Japan, and demonstrated that it could use PET as its sole carbon and energy source. The organism produces two key enzymes — PETase and MHETase — that work sequentially to convert PET into its constituent monomers, terephthalic acid and ethylene glycol. This finding fundamentally changed the scientific understanding of what was biologically possible with synthetic polymers.

Several other bacterial genera have demonstrated meaningful plastic-degrading activity. *Pseudomonas* species are among the most versatile, with documented activity against PE, PU, and other polymers. Their metabolic flexibility, partly mediated through alkane hydroxylase enzyme systems, allows them to engage with the carbon-carbon backbone of polyolefin plastics. *Bacillus subtilis*, *B. cereus*, and related species have been isolated from plastic-contaminated environments worldwide and shown to colonize and degrade PE and PS surfaces under laboratory conditions. *Rhodococcus ruber* has demonstrated measurable PE degradation, particularly when the polymer is pre-treated by UV irradiation to introduce surface oxidation. *Comamonas acidovorans* is implicated in nylon degradation, and *Klebsiella pneumoniae* has shown activity against PU (Restrepo-Flórez *et al.,* 2014). Importantly, the plastisphere — the biofilm community that forms on plastic debris in aquatic environments — contains a distinct and specialized assemblage of bacterial taxa not typically dominant in the surrounding water or sediment. Zettler *et al.,* (2013) characterized the plastisphere as a unique ecological habitat, and subsequent metagenomic analyses have identified within its numerous genes encoding putative plastic-degrading enzymes, suggesting that the plastisphere harbors a substantial, as-yet-untapped reservoir of biodegradation potential.

2. Fungi

Fungi bring a distinct set of capabilities to plastic degradation. Their hyphal growth allows physical penetration of polymer surfaces, creating micro-fractures that increase surface area and facilitate enzymatic access. Their capacity to produce powerful extracellular oxidative enzymes — evolved originally for the decomposition of lignocellulosic plant material — gives them unique activity against aromatic and recalcitrant polymers. White-rot fungi are particularly noteworthy in this regard. Species such as *Phanerochaete chrysosporium*, *Trametes versicolor*, and *Pleurotus ostreatus* produce laccases, manganese peroxidases, and lignin peroxidases that have demonstrated activity against PS, PU, and PE. *Aspergillus tubingensis*, isolated from a plastic waste dump in Islamabad, Pakistan, was found to degrade PU film within a matter of weeks; scanning electron microscopy confirmed physical disruption of the polymer surface, and spectroscopic analysis indicated chemical modification of polymer chains (Khan *et al.,* 2017). *Pestalotiopsis microspora*, an endophytic fungus discovered in the Amazon rainforest, can degrade PU under both aerobic and anaerobic conditions — a finding with practical relevance for degradation in oxygen-limited environments such as landfill interiors (Russell *et al.,* 2011). *Cladosporium* and *Penicillium* species have also been documented with varying degrees of activity against polyolefin and polyester substrates. The filamentous growth strategy of fungi is not only mechanically useful but also ecologically significant. Fungal hyphae can bridge soil particles and plastic fragments, establishing physical connections that facilitate enzyme secretion directly at the polymer interface. This intimate physical association may partly explain why fungi are consistently found within plastisphere communities despite their sometimes-slower generation times compared to bacteria.

3. Algae

Algae and cyanobacteria occupy the photosynthetic tier of plastisphere communities and contribute to plastic degradation through both direct and indirect mechanisms. Their direct enzymatic activity on synthetic polymers is less well characterized than that of bacteria or fungi, but their ecological role in the plastisphere is becoming increasingly recognized. Certain cyanobacteria generate reactive oxygen species (ROS) as byproducts of photosynthetic electron transport. These reactive molecules can attack polymer chains, initiating oxidative degradation that makes surfaces more accessible to heterotrophic bacteria and fungi downstream. In this sense, photosynthetic microorganisms may act as primers in a multi-stage degradation process, preparing the polymer surface for subsequent enzymatic attack by other community members. Algae also shape the physical and chemical microenvironment on plastic surfaces by producing oxygen, altering local pH, and secreting organic compounds that serve as substrates for associated heterotrophs. Studies examining the community composition of plastisphere biofilms consistently find photosynthetic organisms among the early colonizers, suggesting a foundational ecological role. Some green algae, including members of the genus *Chlorella*, have been reported to produce extracellular compounds that promote polymer surface modification, and there is emerging evidence that certain diatom-secreted compounds can interact with plastic surfaces in chemically meaningful ways. The full extent of algal contributions to plastic degradation remains an active area of investigation (Bhatt *et al.,* 2021).

Table 2: Plastic-Degrading Microorganisms and Their Substrates

Organism	**Type**	**Plastic Substrate**	**Key Mechanism**
Ideonella sakaiensis	Bacterium	PET	PETase/MHETase enzymatic hydrolysis
Pseudomonas putida	Bacterium	PE, PU	Alkane hydroxylase, esterase activity
Bacillus cereus	Bacterium	PE, PS	Surface colonization, oxidative degradation
Rhodococcus ruber	Bacterium	PE	Co-metabolic oxidation
Phanerochaete chrysosporium	Fungus	PS, PE, PU	Laccase, lignin peroxidase
Aspergillus tubingensis	Fungus	PU	Esterase, cutinase activity
Pestalotiopsis microspora	Fungus	PU	Serine hydrolase activity (aerobic and anaerobic)
Trametes versicolor	Fungus	PS, PE	Laccase, manganese peroxidase

Mechanisms of Plastic Biodegradation

Plastic biodegradation is not a single event but a sequential, multi-stage process. Understanding each stage provides a clearer picture of how complex synthetic polymers are ultimately converted into simpler biological compounds. The process is generally conceptualized as proceeding through four interconnected stages: biodeterioration, biofragmentation, assimilation, and mineralization.

Biodeterioration

Biodeterioration refers to the initial physical and chemical deterioration of the plastic material caused by the combined action of microorganisms and environmental forces. When a plastic item enters a natural environment, it is rapidly colonized by microorganisms that form biofilm communities on its surface. These communities exert mechanical forces through physical attachment and hyphal penetration (in the case of fungi), producing micro-cracks, surface pitting, and structural weakening of the polymer. Simultaneously, microbial metabolites — including organic acids, biosurfactants, and reactive oxygen species — alter the surface chemistry of the polymer, reducing hydrophobicity, introducing polar functional groups, and increasing wettability. UV radiation, temperature fluctuations, and oxidative weathering contribute to this initial stage alongside biological activity. The net result is a material whose surface is physically disrupted and chemically modified, making it more amenable to the enzymatic processes that follow (Shah *et al.,* 2008).

Biofragmentation

Biofragmentation is the enzymatic cleavage of polymer chains into progressively smaller fragments — oligomers, dimers, and ultimately monomers. This is the biochemically central stage of plastic biodegradation, and the stage that has attracted the greatest scientific attention. Extracellular enzymes secreted by surface-associated microorganisms attack specific chemical bonds within the polymer backbone. For polyesters such as PET, hydrolytic enzymes including PETase, cutinase, and esterase cleave ester bonds through hydrolysis, introducing water molecules to break the covalent linkage between polymer units. For polyolefins such as PE and PP, which lack hydrolyzable bonds, oxidative enzymes including laccases, peroxidases, and alkane hydroxylases attack the carbon–carbon backbone following initial abiotic oxidation. The products of biofragmentation are water-soluble or low-molecular-weight compounds that can be transported across microbial cell membranes for intracellular metabolism (Tokiwa *et al.,* 2009). The rate of biofragmentation is strongly influenced by the physical and chemical properties of the polymer substrate. Crystalline regions are substantially more resistant to enzymatic attack than amorphous regions, because the tightly ordered arrangement of polymer chains in crystalline domains excludes water and limits enzyme access to cleavage sites. High-molecular-weight polymers with few surface-accessible bonds degrade more slowly than lower-molecular-weight or more amorphous forms of the same material.

Assimilation

Assimilation refers to the uptake of plastic degradation products — monomers, dimers, and small oligomers — into microbial cells, where they enter central metabolic pathways and are used as carbon and energy sources for growth and reproduction. This stage is where the polymer-derived carbon actually becomes incorporated into living biomass. Following PET depolymerization, for instance, the monomers terephthalic acid and ethylene glycol are transported into bacterial cells. Terephthalic acid enters the protocatechuate branch of the beta-ketoadipate pathway, a widely distributed bacterial metabolic route for aromatic compound degradation. Ethylene glycol is oxidized through a series of enzymatic steps to glycolate and then glyoxylate, which enters central carbon metabolism. *Ideonella sakaiensis* uses both monomers efficiently as carbon sources, with the complete metabolic pathway for their utilization encoded in its genome (Yoshida *et al.,* 2016). For polyolefin degradation products, assimilation follows the metabolism of fatty acids and alkanes, with the degradation intermediates feeding into beta-oxidation pathways that generate acetyl-CoA for energy production and biosynthesis. The efficiency of assimilation determines how much of the polymer-derived carbon is actually consumed versus how much might accumulate as partially degraded intermediates in the environment.

Mineralization

Mineralization is the final stage, in which assimilated carbon is completely converted to inorganic end products — primarily carbon dioxide and water under aerobic conditions, or carbon dioxide and methane under anaerobic conditions. Nitrogen-, sulfur-, and phosphorus-containing degradation products are similarly converted to inorganic forms. Complete mineralization represents the ultimate environmental fate of biodegradable material, returning the carbon that was originally captured from the atmosphere (as fossil carbon, in the case of conventional plastics) back to the inorganic carbon cycle. In practice, complete mineralization of plastic-derived carbon under natural conditions is rarely rapid. The slow initial stages of depolymerization limit the supply of assimilable substrates, and much of the polymer-derived biomass produced during microbial growth will itself decompose slowly. Nevertheless, mineralization is the benchmark against which biodegradation claims are properly assessed; a material that fragments into microplastics but does not mineralize has not truly biodegraded in an environmentally meaningful sense (Emadian *et al.,* 2017).

Enzymes Involved in Plastic Degradation

Enzymes are the molecular engines of plastic biodegradation. Their specificity, catalytic efficiency, and environmental stability determine the pace and completeness of biological plastic breakdown. The following enzymes have been most extensively characterized in the context of synthetic polymer degradation.

1. PETase

PETase (PET hydrolase) is a serine hydrolase enzyme first described in *Ideonella sakaiensis* that catalyzes the hydrolysis of PET polymer chains at their ester linkages. It cleaves both internal ester bonds (endolytic activity) and terminal bonds (exolytic activity), producing primarily the intermediates mono(2-hydroxyethyl) terephthalate (MHET), bis(2-hydroxyethyl) terephthalate (BHET), and terephthalic acid. Structurally, PETase belongs to the cutinase family of alpha/beta hydrolases and features an active site with a classic catalytic triad of serine, histidine, and aspartate residues. Its unusual ability to accommodate the bulky aromatic PET substrate is attributed to subtle structural features that distinguish it from related cutinases, including a wider active site cleft and modified loop conformations (Austin *et al.,* 2018). Extensive protein engineering has been applied to PETase to improve its catalytic performance. A particularly notable engineered variant, FAST-PETase, was developed through machine learning-guided design and demonstrated the ability to depolymerize high-crystallinity PET films within days at moderate temperatures — a dramatic improvement over the wild-type enzyme (Lu *et al.,* 2022).

2. MHETase

MHETase works in tandem with PETase in *Ideonella sakaiensis*, converting the intermediate product MHET into the final monomers terephthalic acid and ethylene glycol. Without MHETase activity, MHET accumulates and potentially inhibits the activity of PETase, making MHETase an essential functional partner in the complete depolymerization of PET.

Structurally, MHETase is a tannase-family enzyme with a lid domain that covers the active site and contributes to substrate specificity for MHET. Crystallographic studies have revealed the molecular basis for its substrate recognition, which has in turn informed engineering efforts aimed at expanding its activity to related substrates including BHET (Palm *et al.,* 2019). The construction of bifunctional fusion enzymes combining PETase and MHETase activities in a single protein has been pursued as a strategy for enhancing overall PET degradation efficiency. Such fusion proteins can, in principle, process PET degradation intermediates more rapidly by keeping the two enzymatic activities in close proximity, reducing the diffusion distance between sequential reaction steps.

3. Laccases

Laccases are multi-copper oxidase enzymes that catalyze the oxidation of a wide range of organic substrates using molecular oxygen as the terminal electron acceptor, producing water as the only byproduct. They are produced by numerous fungi, many bacteria, and some plants, and have historically been studied for their role in lignin degradation and biosynthesis. In the context of plastic degradation, laccases are particularly relevant for polymers that contain aromatic components or have been oxidatively pre-treated. They have demonstrated activity against PS, PE (particularly UV-pre-treated samples), and various aromatic polymer components. Their mechanism involves the generation of radical intermediates that can initiate chain cleavage and surface oxidation in polymer substrates (Sánchez, 2009). Laccases are attractive for biotechnological applications because they do not require co-factors beyond molecular oxygen, are relatively stable under a range of conditions, and can be produced at scale using fungal fermentation. However, their substrate specificity for specific polymer types is less precise than that of hydrolytic enzymes like PETase, and their degradation products can be more varied and less predictable.

4. Cutinases

Cutinases are serine esterases that were originally identified for their role in the degradation of plant cutin — the polyester that forms the protective outer layer of plant surfaces. Their structural similarity to lipases and esterases, combined with their capacity to act on both soluble and insoluble polyester substrates, makes them highly relevant to plastic degradation research.

Among cutinases, the leaf-branch compost cutinase (LCC), originally identified from a thermophilic compost metagenome, has attracted particular attention for its exceptional thermostability. At temperatures around 65–72°C — at which PET transitions from its semi-crystalline to a more amorphous state — LCC retains high catalytic activity, allowing it to degrade even high-crystallinity PET effectively. An engineered variant, LCCICCG, incorporating four stabilizing mutations, achieved near-complete depolymerization of post-consumer PET under industrially relevant conditions in a landmark study by (Tournier *et al.,* 2020) demonstrating the practical potential of thermostable cutinases for circular plastic recycling. *Thermobifida fusca* cutinase and *Fusarium solani* cutinase are among the other well-studied members of this family, with both having demonstrated activity against PET, PLA, and related polyester substrates under laboratory conditions.

Factors Affecting Biodegradation

Several environmental and material conditions collectively determine how fast and completely a plastic break down biologically.

1. Temperature

Temperature influences both microbial metabolism and polymer accessibility. Most plastic-degrading microorganisms work best between 25–45°C, where enzymatic activity is efficient without causing protein breakdown. For PET specifically, working near its glass transition temperature (67–80°C) loosens the polymer structure and dramatically improves enzyme penetration — the key reason thermostable enzymes like LCC variants are so valued in industrial applications (Tournier *et al.,* 2020). Even in cold environments, psychrophilic microorganisms have been found actively colonizing plastic debris, demonstrating that biodegradation potential exists across a wide thermal range (Urbanek *et al.,* 2018).

2. pH

Most plastic-degrading enzymes perform optimally between pH 6.0 and 8.0. Outside this range, enzyme structures destabilize and substrate binding weakens. pH also determines which microbial communities colonize plastic surfaces, since acid-tolerant and alkaline-tolerant organisms carry different enzymatic toolkits. In industrial systems, buffered conditions are maintained throughout processing to sustain consistent enzyme activity. A useful bonus: mildly alkaline conditions promote chemical hydrolysis of ester bonds even without enzymatic help, complementing biological activity.

3. Oxygen Availability

Aerobic conditions support the most efficient plastic degradation, enabling full oxidative metabolism with carbon dioxide and water as end products. In oxygen-limited environments such as landfill interiors or waterlogged sediments, degradation slows considerably and anaerobic communities produce methane instead. For polyesters like PET, the initial enzymatic hydrolysis step does not require oxygen directly, but the complete breakdown of released monomers is significantly faster under aerobic conditions.

4. Polymer Properties

The physical and chemical nature of the plastic itself is arguably the strongest determinant of how readily it biodegrades. Crystallinity is the most critical factor — tightly packed crystalline regions block enzyme access, while amorphous regions degrade far more readily. Higher molecular weight, chemical additives such as UV stabilizers and flame retardants, and the inherent hydrophobicity of most plastics all create additional barriers to enzymatic attack. Surface area, by contrast, works in favor of degradation — fragmentation, UV pre-treatment, or using thin films all increase enzyme-accessible surface, meaningfully accelerating the process.

Conclusion

The challenge of plastic pollution is inseparable from the challenge of building a sustainable relationship between human industrial activity and the natural systems upon which all life depends. Synthetic plastics have delivered extraordinary practical value, but their accumulation in the environment — as macro-debris and as pervasive microplastic particles — represents a debt that is now coming due. Conventional waste management approaches have proven insufficient, and the scale of the problem continues to grow faster than current solutions can address it. Microbial bioremediation offers a scientifically grounded and increasingly practical component of the response. The diversity of plastic-degrading bacteria, fungi, and algae; the growing catalogue of characterized degradation enzymes; the advances in metagenomics, protein engineering, synthetic biology, and systems biology; and the emerging examples of pilot-scale enzymatic recycling all testify to the genuine and growing capacity of biological science to contribute to this challenge. Enzymes such as PETase, cutinase, laccase, and MHETase, along with the organisms that produce them, represent tools of remarkable specificity and potential whose full capabilities are only beginning to be understood and harnessed. At the same time, intellectual honesty requires acknowledging that bioremediation is not a sufficient response on its own. Slow degradation rates, scale-up complexity, economic constraints, and the sheer magnitude of accumulated plastic pollution mean that biological solutions must be paired with reduced production, improved collection infrastructure, expanded mechanical recycling, and strong policy frameworks. The most productive vision is an integrated one, in which microbial and enzymatic tools occupy their appropriate niche within a comprehensive strategy — handling the plastic streams that other approaches cannot manage effectively, recovering valuable materials through biological depolymerization, and gradually reducing the environmental legacy of the synthetic polymer age.

References

1. Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin, 62*(8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030
2. Austin, H. P., Allen, M. D., Donohoe, B. S., Rorrer, N. A., Kearns, F. L., Silveira, R. L., … & Beckham, G. T. (2018). Characterization and engineering of a plastic-degrading aromatic polyesterase. *Proceedings of the National Academy of Sciences, 115*(19), E4350–E4357. https://doi.org/10.1073/pnas.1718804115
3. Bhatt, P., Pathak, V. M., Joshi, S., Bisht, T. S., Singh, K., & Chandra, D. (2021). Microbial degradation of microplastics and the pivotal role of plastisphere biodiversity. *Science of the Total Environment, 793*, 148544.
4. Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of microplastic on shorelines worldwide: Sources and sinks. *Environmental Science & Technology, 45*(21), 9175–9179. https://doi.org/10.1021/es201811s
5. Danso, D., Schmeisser, C., Chow, J., Zimmermann, W., Wei, R., Leggewie, C., Li, X., Hazen, T., & Streit, W. R. (2018). New insights into the function and global distribution of polyethylene terephthalate (PET)-degrading bacteria and enzymes in marine and terrestrial metagenomes. *Applied and Environmental Microbiology, 84*(8), e02773-17. https://doi.org/10.1128/AEM.02773-17
6. Emadian, S. M., Onay, T. T., & Demirel, B. (2017). Biodegradation of bioplastics in natural environments. *Waste Management, 59*, 526–536. https://doi.org/10.1016/j.wasman.2016.10.006
7. Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances, 3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782
8. Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science, 347*(6223), 768–771. https://doi.org/10.1126/science.1260352
9. Khan, S., Nadir, S., Shah, Z. U., Shah, A. A., Karunarathna, S. C., Xu, J., … & Hasan, F. (2017). Biodegradation of polyester polyurethane by *Aspergillus tubingensis*. *Environmental Pollution, 225*, 469–480. https://doi.org/10.1016/j.envpol.2017.03.012

10. Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International, 163*, 107199. https://doi.org/10.1016/j.envint.2022.107199
11. Lu, H., Diaz, D. J., Czarnecki, N. J., Zhu, C., Kim, W., Shroff, R., … & Ellington, A. D. (2022). Machine learning-aided engineering of hydrolases for PET depolymerization. *Nature, 604*(7907), 662–667. https://doi.org/10.1038/s41586-022-04599-z
12. Palm, G. J., Reisky, L., Böttcher, D., Müller, H., Michels, E. A. P., Walczak, M. C., … & Bornscheuer, U. T. (2019). Structure of the plastic-degrading *Ideonella sakaiensis* MHETase bound to a substrate. *Nature Communications, 10*(1), 1717. https://doi.org/10.1038/s41467-019-09326-3
13. Restrepo-Flórez, J. M., Bassi, A., & Thompson, M. R. (2014). Microbial degradation and deterioration of polyethylene: A review. *International Biodeterioration & Biodegradation, 88*, 83–90. https://doi.org/10.1016/j.ibiod.2013.12.014
14. Rillig, M. C., Ziersch, L., & Hempel, S. (2017). Microplastic transport in soil by earthworms. *Scientific Reports, 7*(1), 1362. https://doi.org/10.1038/s41598-017-01594-7
15. Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports, 3*, 3263. https://doi.org/10.1038/srep03263
16. Rujnić-Sokele, M., & Pilipović, A. (2017). Challenges and opportunities of biodegradable plastics: A mini review. *Waste Management & Research, 35*(2), 132–140. https://doi.org/10.1177/0734242X16683272
17. Russell, J. R., Huang, J., Anand, P., Kucera, K., Sandoval, A. G., Dantzler, K. W., … & Strobel, S. A. (2011). Biodegradation of polyester polyurethane by endophytic fungi. *Applied and Environmental Microbiology, 77*(17), 6076–6084. https://doi.org/10.1128/AEM.00521-11
18. Sánchez, C. (2009). Lignocellulosic residues: Biodegradation and bioconversion by fungi. *Biotechnology Advances, 27*(2), 185–194. https://doi.org/10.1016/j.biotechadv.2008.11.001
19. Shah, A. A., Hasan, F., Hameed, A., & Ahmed, S. (2008). Biological degradation of plastics: A comprehensive review. *Biotechnology Advances, 26*(3), 246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005
20. Thompson, R. C., Swan, S. H., Moore, C. J., & vom Saal, F. S. (2009). Our plastic age. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1526), 1973–1976. https://doi.org/10.1098/rstb.2009.0054

21. Tokiwa, Y., Calabia, B. P., Ugwu, C. U., & Aiba, S. (2009). Biodegradability of plastics. *International Journal of Molecular Sciences, 10*(9), 3722–3742. https://doi.org/10.3390/ijms10093722
22. Tournier, V., Topham, C. M., Gilles, A., David, B., Folgoas, C., Moya-Leclair, E., … & Marty, A. (2020). An engineered PET depolymerase to break down and recycle plastic bottles. *Nature, 580*(7802), 216–219. https://doi.org/10.1038/s41586-020-2149-4
23. Urbanek, A. K., Rymowicz, W., & Mirończuk, A. M. (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Applied Microbiology and Biotechnology, 102*(18), 7669–7678. https://doi.org/10.1007/s00253-018-9195-y
24. Wei, R., & Zimmermann, W. (2017). Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: How far are we? *Microbial Biotechnology, 10*(6), 1308–1322. https://doi.org/10.1111/1751-7915.12710
25. Wilkes, R. A., & Aristilde, L. (2017). Degradation and metabolism of synthetic plastics and associated products by *Pseudomonas* sp.: Capabilities and challenges. *Journal of Applied Microbiology, 123*(3), 582–593. https://doi.org/10.1111/jam.13472
26. Wright, S. L., & Kelly, F. J. (2017). Plastic and human health: A micro issue? *Environmental Science & Technology, 51*(12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423
27. Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., … & Oda, K. (2016). A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science, 351*(6278), 1196–1199. https://doi.org/10.1126/science.aad6359
28. Zettler, E. R., Mincer, T. J., & Amaral-Zettler, L. A. (2013). Life in the "plastisphere": Microbial communities on plastic marine debris. *Environmental Science & Technology, 47*(13), 7137–7146. https://doi.org/10.1021/es401288x

A COMPREHENSIVE REVIEW ON ARSENIC AND ITS EFFECT ON HUMAN HEALTH

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Abstract

Elevated concentrations of arsenic in groundwater pose a public health threat to millions of people worldwide, including severely affected populations in South and Southeast Asia. While arsenic is an established human carcinogen and has been associated with a multitude of health outcomes in epidemiologic studies, a mode of action has yet to be determined for some aspects of arsenic toxicity. Herein, we emphasize the role of recent genetic and molecular epidemiologic investigations of arsenic toxicity. Additionally, we discuss considerations for the public health impacts of arsenic exposure through drinking water with respect to primary and secondary prevention efforts.

Keywords: Arsenic, Drinking Water, Human Health.

Introduction

Arsenic is a naturally occurring metalloid, ubiquitously present in the environment. Through reduction-oxidation reactions, arsenic can be released from soil and rock into the surrounding aquifers. Elevated concentrations of arsenic in groundwater were first realized in West Bengal, India, and Bangladesh in the 1980s and 1990s with the appearance of skin lesion epidemics in villages, which accessed drinking water by tubewells that tap into the arsenic-enriched aquifers (1). The tubewells were installed through governmental and public health initiatives beginning in the 1970s to provide microbially-safe drinking water to the population through the consumption of groundwater. This was an effort to reduce mortality and morbidity from cholera and other waterborne diseases that had plagued the population, and proved to be effective towards this end with the subsequent reduction of infant mortality. Most recently, additional regions of South and Southeast Asia have been determined to have elevated concentrations of arsenic in groundwater used for human consumption (2). In 1993, the World Health Organization revised its guideline for the permissible concentration of arsenic in drinking water from 50 µg/L to 10 µg/L, which was also the maximum permissible concentration of arsenic in drinking water adopted by the United States Environmental Protection Agency in 2001 as well as several other developed countries (3). However, the permissible level of arsenic in drinking water regulated by several developing countries in South and Southeast Asia, including Bangladesh, Cambodia, China, India, Lao People's Democratic Republic, Myanmar, Nepal, and Pakistan, is still 50 µg/L. There has not been reliable data to quantify the global burden of arsenic in drinking water worldwide; however, arsenic in drinking water has been detected at concentrations greater than 10 µg/L or the prevailing national standard in several countries including Argentina, Australia, Bangladesh, Cambodia, Chile, China, Hungary, India, Lao People's Democratic Republic, Mexico, Myanmar, Nepal, Pakistan, Peru, Thailand, United States, and Vietnam (2, 4). Globally, nearly 100 million people are chronically exposed to arsenic through naturally contaminated drinking water (5), with the largest affected population in Bangladesh (6).

Arsenic and Human Health

The International Agency for Research on Cancer has classified arsenic as a class I human carcinogen (7). Arsenic in drinking water has been associated with increased risk of a wide range of health outcomes including cancers of the skin, lung, bladder, liver, and kidney (8– 12), neurological disease (13), cardiovascular disease (14), as well as other non-malignant diseases (15, 16).

While arsenic is a well-established human carcinogen (17) and has additionally been associated with an array of chronic diseases through epidemiologic investigations (12, 18– 30), the underlying mechanism(s) of some aspects of arsenic toxicity has not yet been determined. This is largely due to the absence of a suitable animal model for the evaluation of arsenic toxicity (31, 32). Additionally, while the health effects of arsenic exposure through drinking water have been well established at higher doses (>100 µg/L), evidence on the effects of arsenic at low-to-moderate levels of exposure is not well established. Arsenic exposure at low-to-moderate levels is more prevalent than high-level exposure, and even a small increased risk may translate to a large number of excess cases and be of public health concern. Epidemiologic investigations of health effects at these lower arsenic concentrations are of potentially substantial public health relevance for both developed and developing nations worldwide in providing a better basis for planning population interventions and policy decisions.

While the mechanisms of arsenic toxicity have yet to be established, recent advances have been made in arsenic epidemiology with the use of genetic and molecular techniques to shed light on the underlying mechanisms of arsenic toxicity.

Recent Findings from Genetic and Molecular Epidemiology Arsenic Metabolism

Arsenic is primarily present in the inorganic form (arsenate and arsenite) in drinking water (33). Once internalized, it goes through a series of reduction and oxidative methylation steps (34).

While methylation of an exogenous compound is typically considered to be a detoxification process, there is mounting evidence that the partial methylation of arsenic may increase its toxicity in vivo particularly via the trivalent monomethylated arsenic species that is more toxic than the inorganic and pentavalent methylated arsenic species (35–38). Ingested inorganic arsenic is typically excreted as 10– 20% inorganic arsenic, 10–15% monomethylated arsenic (MMA), and 60–75% dimethylated arsenic (DMA) (39). However, there is known inter-individual variability in the methylation capacity of arsenic (as reviewed in (40)), which has been hypothesized to partly explain the variability in susceptibility to arsenic toxicity.

Recently, the first genomewide association study (GWAS) of arsenic-related metabolism and toxicity phenotypes was conducted (41), which utilized data on urinary arsenic metabolite concentrations and 259,597 genomewide single nucleotide polymorphisms (SNPs) for 1,313 arsenic-exposed Bangladeshi individuals. Five SNPs (rs4919694, rs9527, rs4290163, rs11191527, and rs11191659) near the AS3MT gene (arsenite methyltransferase; 10q24.32) showed significant independent associations for urinary total MMA percent and total DMA percent. Furthermore, the authors showed that one of the SNPs (rs9527) was associated with skin lesion risk through case-control comparison (41). While the role of AS3MT in arsenic metabolism has been previously described (42), two novel SNPs (rs9527 and rs11191527) not strongly correlated with any previously reported SNPs were identified.

Genetic susceptibility to arsenic-related health outcomes has been evaluated by several candidate gene studies in the last decade (43). Despite this, the limited scope of work that has been done to evaluate genetic susceptibility to arsenic toxicity clearly warrants further investigation. Additional GWAS and replication studies will hopefully overcome obstacles in the existing literature including inconsistencies in case definitions, differences in arsenic exposure distributions across populations as well as other covariates, and under-powered studies to be able to synthesize genetic risk factors of arsenic toxicity from future research.

Biological Responses of Prenatal Arsenic Exposure

The health effects of prenatal arsenic exposure have been recently reviewed by Vahter (44). There is increasing epidemiologic evidence of the association of infant growth and mortality with prenatal arsenic exposure; however, the question still remains regarding later life health effects of prenatal and early life arsenic exposure (45). Few epidemiologic studies have evaluated health outcomes in relation to early life arsenic exposure (46–48), although there is some evidence from research in Chile of increased mortality rates associated with prenatal and early life arsenic exposure (46). Molecular biomarkers of early biological effects have been increasingly studied in arsenic epidemiology to elucidate information on toxicity mechanisms and biological pathways. The examination of cellular and molecular responses associated with prenatal arsenic exposure is a first step in a life course approach to evaluate early childhood exposure with potential later-life health outcomes.

Public Health Implications

The worldwide prevalence of arsenic in drinking water illustrates the fact that arsenic exposure is a major public health concern deserving attention. There are two major public health considerations with respect to arsenic exposure, which we describe in the context of primary and secondary prevention.

➢ Primary Prevention

Arsenic mitigation is a critical public health need in exposed populations, with progress being made toward eliminating arsenic exposure through drinking water sources in the human population. Mitigation efforts have largely taken two forms in arsenic exposed populations: well-switching and arsenic removal technologies. One of the approaches to mitigation taken in the Araihazar region of Bangladesh has focused on taking advantage of the high degree of spatial variability of arsenic in groundwater, the consequence of which is that a majority of residents in the area live within walking distance of a tubewell that is low in arsenic (52). Surveys as well as time-series measurements of urinary arsenic have shown that reporting the results of tubewell testing, along with education on the health risks of arsenic in drinking water, has led a substantial portion of households to switch to a nearby low-arsenic well, markedly reducing exposure to arsenic throughout the geographic study area (53, 54). In areas with little opportunity for sharing existing low arsenic wells, the installation of community wells by a local organization has been facilitated, tapping deeper low-arsenic aquifers (55). However, despite the discovery of arsenic-enriched groundwater in South and Southeast Asia, new wells continue to be installed blindly without regard to possible arsenic contamination. Observations from Bangladesh indicate that a large proportion of new tubewells that are installed are not immediately tested for their arsenic concentration; thus, there is the continuous need for testing of new tubewells which can be reliably achieved through field kits (56).

Arsenic removal technologies are another mitigation strategy employed in arsenic exposed regions of South and Southeast Asia. A comprehensive review of arsenic removal technologies has recently been conducted by Jain and Singh (57). There are complex interactions and logistical considerations that should be considered for the large-scale implementation of arsenic removal technologies in populations including the selection of a technology appropriate for the concentration of arsenic found in the groundwater, the economic condition and feasibility of the technology for the population, the population distribution in the geographic area, the technology and labor skill available for the technology operation and maintenance in the population, and environmental impacts (58). Besides the complication of properly maintaining arsenic removal technologies at the household or community level, there is also concern about the likelihood of microbial contamination of filtration systems in regions where sanitation is still very poor.

➢ Secondary Prevention

The second major public health consideration is preventing or reducing harm after chronic arsenic exposure has occurred. While there is substantial evidence of dose-response associations between arsenic in drinking water and various health outcomes, studies have shown that remediation of arsenic exposure alone does not reduce arsenic-related health risks in the population (59–61). In recent publications using prospective data from the Health Effects of Arsenic Longitudinal Study cohort, it was shown utilizing repeated measures of urinary total arsenic exposure over time that once chronically exposed, a reduction of decreasing exposure for a short amount of time did not reduce one's risk of mortality (59) or skin lesion incidence (62). Furthermore, studies from Taiwan and Chile indicate that elevated cancer risk among arsenic exposed populations persists for at least several decades after cessation of exposure (19, 63, 64). Therefore, evidence from these prior studies suggests that it may be important to consider other health prevention and promotion strategies in conjunction with remediation for arsenic-exposed populations. Evaluation of genetic determinants of arsenic-related health outcomes as well as epigenetic modifications associated with exposure could contribute to a greater understanding of the genetic and molecular pathways that underlie arsenic toxicity and may inform future interventions and secondary prevention strategies of arsenic-exposed populations. In addition to elucidating biological mechanisms of action, investigating genetic susceptibility may help identify individuals with higher risk to arsenic-related toxicity, aiding in secondary prevention and intervention of arsenic-exposed populations.

Conclusion

Estimation of the future public health burden of arsenic exposure through drinking water has been primarily extrapolated from data from other populations. While the exact magnitude of these estimates may be uncertain, it is clear that millions of individuals in South and Southeast Asia are at increased risk of arsenic-related diseases and mortality. Future public health research should emphasize arsenic mitigation in the most severely affected regions. Additionally, future molecular and genetic epidemiologic findings may have potential translational implications for prevention and treatment of arsenic-associated toxicities worldwide.

References

1. Dhar, R., Biswas, B., Samanta, G., Mandal, B., Chakraborti, D., Roy, S. (1997). Groundwater arsenic calamity in Bangladesh. *Current Science, 73*(1), 48–59.
2. McCarty, K. M., Hanh, H. T., & Kim, K. W. (2011). Arsenic geochemistry and human health in South East Asia. *Reviews on Environmental Health, 26*(1), 71–78.
3. EPA. (2001). *Arsenic and clarifications to compliance and new source monitoring rule: A quick reference guide*. Retrieved May 11, 2012, from http://water.epa.gov/drink/info/arsenic/upload/2005_11_10_arsenic_quickguide.pdf
4. British Geological Survey (BGS), & Department of Public Health Engineering (DPHE). (2001). *Arsenic contamination of groundwater in Bangladesh* (BGS Technical Report WC/00/19, Vol. 2). Keyworth: British Geological Survey.
5. Ng, J. C., Wang, J., & Shraim, A. (2003). A global health problem caused by arsenic from natural sources. *Chemosphere, 52*(9), 1353–1359.
6. Smith, A. H., Lingas, E. O., & Rahman, M. (2000). Contamination of drinking-water by arsenic in Bangladesh: A public health emergency. *Bulletin of the World Health Organization, 78*(9), 1093–1103.
7. International Agency for Research on Cancer. (1987). *IARC monographs on the evaluation of carcinogenic risks to humans: Arsenic and arsenic compounds*. Lyon, France: Author.
8. Smith, A. H., Goycolea, M., Haque, R., & Biggs, M. L. (1998). Marked increase in bladder and lung cancer mortality in a region of Northern Chile due to arsenic in drinking water. *American Journal of Epidemiology, 147*(7), 660–669.
9. Chen, C. J., Chen, C. W., Wu, M. M., & Kuo, T. L. (1992). Cancer potential in liver, lung, bladder and kidney due to ingested inorganic arsenic in drinking water. *British Journal of Cancer, 66*(5), 888–892.
10. Hopenhayn-Rich, C., Biggs, M. L., Fuchs, A., Bergoglio, R., Tello, E. E., Nicolli, H., et al. (1996). Bladder cancer mortality associated with arsenic in drinking water in Argentina. *Epidemiology, 7*(2), 117–124.
11. Hopenhayn-Rich, C., Biggs, M. L., & Smith, A. H. (1998). Lung and kidney cancer mortality associated with arsenic in drinking water in Cordoba, Argentina. *International Journal of Epidemiology, 27*(4), 561–569.
12. Tseng, W. P. (1977). Effects and dose-response relationships of skin cancer and blackfoot disease with arsenic. *Environmental Health Perspectives, 19*, 109–119.

13. Brouwer, O. F., Onkenhout, W., Edelbroek, P. M., de Kom, J. F., de Wolff, F. A., & Peters, A. C. (1992). Increased neurotoxicity of arsenic in methylenetetrahydrofolate reductase deficiency. *Clinical Neurology and Neurosurgery, 94*(4), 307–310.
14. Wu, M. M., Kuo, T. L., Hwang, Y. H., & Chen, C. J. (1989). Dose-response relation between arsenic concentration in well water and mortality from cancers and vascular diseases. *American Journal of Epidemiology, 130*(6), 1123–1132.
15. Rahman, M., Tondel, M., Ahmad, S. A., Chowdhury, I. A., Faruquee, M. H., & Axelson, O. (1999). Hypertension and arsenic exposure in Bangladesh. *Hypertension, 33*(1), 74–78.
16. Heck, J. E., Chen, Y., Grann, V. R., Slavkovich, V., Parvez, F., & Ahsan, H. (2008). Arsenic exposure and anemia in Bangladesh: A population-based study. *Journal of Occupational and Environmental Medicine, 50*(1), 80–87.
17. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. (2004). *Some drinking-water disinfectants and contaminants, including arsenic* (Vol. 84). Lyon, France: International Agency for Research on Cancer.
18. Smith, A. H., Goycolea, M., Haque, R., & Biggs, M. L. (1998). Marked increase in bladder and lung cancer mortality in a region of Northern Chile due to arsenic in drinking water. *American Journal of Epidemiology, 147*(7), 660–669.
19. Chen, C. J., Chen, C. W., Wu, M. M., & Kuo, T. L. (1992). Cancer potential in liver, lung, bladder and kidney due to ingested inorganic arsenic in drinking water. *British Journal of Cancer, 66*(5), 888–892.
20. Hopenhayn-Rich, C., Biggs, M. L., Fuchs, A., Bergoglio, R., Tello, E. E., Nicolli, H., et al. (1996). Bladder cancer mortality associated with arsenic in drinking water in Argentina. *Epidemiology, 7*(2), 117–124.
21. Hopenhayn-Rich, C., Biggs, M. L., & Smith, A. H. (1998). Lung and kidney cancer mortality associated with arsenic in drinking water in Cordoba, Argentina. *International Journal of Epidemiology, 27*(4), 561–569.
22. Brouwer, O. F., Onkenhout, W., Edelbroek, P. M., de Kom, J. F., de Wolff, F. A., & Peters, A. C. (1992). Increased neurotoxicity of arsenic in methylenetetrahydrofolate reductase deficiency. *Clinical Neurology and Neurosurgery, 94*(4), 307–310.
23. Navas-Acien, A., Sharrett, A. R., Silbergeld, E. K., Schwartz, B. S., Nachman, K. E., Burke, T. A., et al. (2005). Arsenic exposure and cardiovascular disease: A systematic review of the epidemiologic evidence. *American Journal of Epidemiology, 162*(11), 1037–1049.

24. States, J. C., Srivastava, S., Chen, Y., & Barchowsky, A. (2009). Arsenic and cardiovascular disease. *Toxicological Sciences, 107*(2), 312–323.
25. Tseng, C. H. (2008). Cardiovascular disease in arsenic-exposed subjects living in the arseniasis-hyperendemic areas in Taiwan. *Atherosclerosis, 199*(1), 12–18.
26. Ahmad, S. A., Sayed, M. H., Barua, S., Khan, M. H., Faruquee, M. H., Jalil, A., et al. (2001). Arsenic in drinking water and pregnancy outcomes. *Environmental Health Perspectives, 109*(6), 629–631.
27. Milton, A. H., Smith, W., Rahman, B., Hasan, Z., Kulsum, U., Dear, K., et al. (2005). Chronic arsenic exposure and adverse pregnancy outcomes in Bangladesh. *Epidemiology, 16*(1), 82–86.
28. von Ehrenstein, O. S., Guha Mazumder, D. N., Hira-Smith, M., Ghosh, N., Yuan, Y., Windham, G., et al. (2006). Pregnancy outcomes, infant mortality, and arsenic in drinking water in West Bengal, India. *American Journal of Epidemiology, 163*(7), 662–669.
29. Milton, A. H., & Rahman, M. (2002). Respiratory effects and arsenic contaminated well water in Bangladesh. *International Journal of Environmental Health Research, 12*(2), 175–179.
30. Parvez, F., Chen, Y., Brandt-Rauf, P. W., Bernard, A., Dumont, X., Slavkovich, V., et al. (2008). Nonmalignant respiratory effects of chronic arsenic exposure from drinking water among never-smokers in Bangladesh. *Environmental Health Perspectives, 116*(2), 190–195.
31. Rossman, T. G. (2003). Mechanism of arsenic carcinogenesis: An integrated approach. *Mutation Research, 533*(1–2), 37–65.
32. Tokar, E. J., Benbrahim-Tallaa, L., Ward, J. M., Lunn, R., Sams, R. L., 2nd, & Waalkes, M. P. (2010). Cancer in experimental animals exposed to arsenic and arsenic compounds. *Critical Reviews in Toxicology, 40*(10), 912–927.
33. Andreae, M. O. (1977). Determination of arsenic species in natural waters. *Analytical Chemistry, 49*(6), 820–823.
34. Aposhian, H. V. (1997). Enzymatic methylation of arsenic species and other new approaches to arsenic toxicity. *Annual Review of Pharmacology and Toxicology, 37*, 397–419.
35. Le, X. C., Ma, M., Cullen, W. R., Aposhian, H. V., Lu, X., & Zheng, B. (2000). Determination of monomethylarsonous acid, a key arsenic methylation intermediate, in human urine. *Environmental Health Perspectives, 108*(11), 1015–1018.

36. Del Razo, L. M., Styblo, M., Cullen, W. R., & Thomas, D. J. (2001). Determination of trivalent methylated arsenicals in biological matrices. *Toxicology and Applied Pharmacology, 174*(3), 282–293.
37. Ahmad, S., Anderson, W. L., & Kitchin, K. T. (1999). Dimethylarsinic acid effects on DNA damage and oxidative stress related biochemical parameters in B6C3F1 mice. *Cancer Letters, 139*(2), 129–135.
38. Styblo, M., Drobna, Z., Jaspers, I., Lin, S., & Thomas, D. J. (2002). The role of biomethylation in toxicity and carcinogenicity of arsenic: A research update. *Environmental Health Perspectives, 110*(Suppl. 5), 767–771.
39. Hopenhayn-Rich, C., Smith, A. H., & Goeden, H. M. (1993). Human studies do not support the methylation threshold hypothesis for the toxicity of inorganic arsenic. *Environmental Research, 60*(2), 161–177.
40. Tseng, C. H. (2009). A review on environmental factors regulating arsenic methylation in humans. *Toxicology and Applied Pharmacology, 235*(3), 338–350.
41. Pierce, B. L., Kibriya, M. G., Tong, L., Jasmine, F., Argos, M., Roy, S., et al. (2012). Genome-wide association study identifies chromosome 10q24.32 variants associated with arsenic metabolism and toxicity phenotypes in Bangladesh. *PLoS Genetics, 8*(2), e1002522.
42. Hernandez, A., Xamena, N., Surralles, J., Sekaran, C., Tokunaga, H., Quinteros, D., et al. (2008). Role of the Met(287)Thr polymorphism in the AS3MT gene on the metabolic arsenic profile. *Mutation Research, 637*(1–2), 80–92.
43. Hernandez, A., & Marcos, R. (2008). Genetic variations associated with interindividual sensitivity in the response to arsenic exposure. *Pharmacogenomics, 9*(8), 1113–1132.
44. Vahter, M. (2008). Health effects of early life exposure to arsenic. *Basic & Clinical Pharmacology & Toxicology, 102*(2), 204–211.
45. Vahter, M. (2009). Effects of arsenic on maternal and fetal health. *Annual Review of Nutrition, 29*, 381–399.
46. Liaw, J., Marshall, G., Yuan, Y., Ferreccio, C., Steinmaus, C., & Smith, A. H. (2008). Increased childhood liver cancer mortality and arsenic in drinking water in northern Chile. *Cancer Epidemiology, Biomarkers & Prevention, 17*(8), 1982–1987.
47. Lindberg, A. L., Rahman, M., Persson, L. Å., & Vahter, M. (2008). The risk of arsenic-induced skin lesions in Bangladeshi men and women is affected by arsenic metabolism and the age at first exposure. *Toxicology and Applied Pharmacology, 230*(1), 9–16.

48. Rahman, M., Vahter, M., Sohel, N., Yunus, M., Wahed, M. A., Streatfield, P. K., et al. (2006). Arsenic exposure and age- and sex-specific risk for skin lesions: A population-based case-referent study in Bangladesh. *Environmental Health Perspectives, 114*(12), 1847–1852.
49. Fry, R. C., Navasumrit, P., Valiathan, C., Svensson, J. P., Hogan, B. J., Luo, M., et al. (2007). Activation of inflammation/NF-kappaB signaling in infants born to arsenic-exposed mothers. *PLoS Genetics, 3*(11), e207.
50. Argos, M., Kibriya, M. G., Parvez, F., Jasmine, F., Rakibuz-Zaman, M., & Ahsan, H. (2006). Gene expression profiles in peripheral lymphocytes by arsenic exposure and skin lesion status in a Bangladeshi population. *Cancer Epidemiology, Biomarkers & Prevention, 15*(7), 1367–1375.
51. Intarasunanont, P., Navasumrit, P., Woraprasit, S., Chaisatra, K., Suk, W. A., Mahidol, C., et al. (2012). Effects of arsenic exposure on DNA methylation in cord blood samples from newborn babies and in a human lymphoblast cell line. *Environmental Health, 11*(1), 31.
52. Van Geen, A., Ahsan, H., Horneman, A. H., Dhar, R. K., Zheng, Y., Hussain, I., et al. (2002). Promotion of well-switching to mitigate the current arsenic crisis in Bangladesh. *Bulletin of the World Health Organization, 80*(9), 732–737.
53. Chen, Y., van Geen, A., Graziano, J. H., Pfaff, A., Madajewicz, M., Parvez, F., et al. (2007). Reduction in urinary arsenic levels in response to arsenic mitigation efforts in Araihazar, Bangladesh. *Environmental Health Perspectives, 115*(6), 917–923.
54. Madajewicz, M., Pfaff, A., van Geen, A., Graziano, J., Hussein, I., Momotaj, H., et al. (2007). Can information alone change behavior? Response to arsenic contamination of groundwater in Bangladesh. *Journal of Development Economics, 84*, 731–754.
55. Van Geen, A., Ahmed, K. M., Seddique, A. A., & Shamsudduha, M. (2003). Community wells to mitigate the arsenic crisis in Bangladesh. *Bulletin of the World Health Organization, 81*(9), 632–638.
56. George, C. M., Graziano, J. H., Mey, J. L., & van Geen, A. (2012). Impact on arsenic exposure of a growing proportion of untested wells in Bangladesh. *Environmental Health, 11*, 7.
57. Jain, C. K., & Singh, R. D. (2012). Technological options for the removal of arsenic with special reference to South East Asia. *Journal of Environmental Management, 107*, 1–18.
58. Kim, K. W., Chanpiwat, P., Hanh, H. T., Phan, K., & Sthiannopkao, S. (2011). Arsenic geochemistry of groundwater in Southeast Asia. *Frontiers of Medicine, 5*(4), 420–433.

CRYOPRESERVATION IN AQUACULTURE: PRINCIPLES, TECHNIQUES AND APPLICATIONS

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Abstract

Cryopreservation, the preservation of biological materials at ultra-low temperatures, offers a powerful tool for advancing aquaculture and conserving fish genetic resources. This chapter explores the principles, methods and applications of fish sperm cryopreservation. It details the critical steps involved, from milt collection and evaluation to freezing, storing and thawing, emphasizing the importance of optimal freezing and thawing rates to minimize cryoinjuries. The chapter discusses the role of extenders and cryoprotectants in maintaining sperm viability, highlighting various types and their specific applications across different fish species. Different cryopreservation techniques, including short-term and long-term storage, are examined, along with detailed protocols for each phase. The chapter further emphasizes the benefits of cryopreservation in aquaculture, such as wider gamete distribution, reduced broodstock maintenance, extended seed availability, selective breeding programs and genetic resource conservation. Finally, it acknowledges the limitations of current cryopreservation techniques, particularly for embryos and oocytes and discusses potential future directions in this field.

Keywords: Cryopreservation, Milt, Extender, Cryoprotectants, Cryoinjuries.

1. Introduction

Aquaculture is a leading sector in aquatic animal production. However, challenges such as inbreeding depression, genetic drift and introgressive hybridization negatively affect the production of high-quality seeds. Cryopreservation offers a solution to these issues and plays a significant role in producing quality seeds and genetically improved varieties. It is also a key strategy for conserving fish genetic resources (Betsy *et al.,* 2021). Cryopreservation involves the long-term storage of biological material without degradation, potentially for thousands of years. This technique ensures the preservation and storage of both maternal and paternal gametes, providing a reliable source of fish genetic material for scientific research, aquaculture and biodiversity conservation. The successful cryopreservation of fish sperm has been achieved in over 200 species, with many species being suitable for cryobanking purposes (Tsai & Lin, 2012).

The term "cryopreservation" originates from the Greek word *kryos*, meaning frost. It refers to the preservation of biological tissues at sub-zero temperatures, typically at -196°C. At these temperatures, all biological activities within cells and tissues are halted, effectively suspending their processes. This technique allows for extended storage durations (Kleeberger *et al.,* 1999).

Cryopreservation is a technique used to freeze cells and tissues at extremely low temperatures, typically at -196°C in liquid nitrogen. It can also be carried out using:

- Solid carbon dioxide (at -79°C)
- Low-temperature deep freezers (at -80°C)
- Vapor-phase nitrogen (at -150°C). (Nazim et al,.)

2. Principle of Cryopreservation

Cryopreservation involves three key steps:

i. Freezing
ii. Storing
iii. Thawing

If proper precautions are not followed, sperm cells may die due to cryoinjuries. These injuries can result from ice crystal formation during freezing and thawing or from osmotic changes. Basic principles of cryopreservation is the rates of freezing and thawing are crucial for maintaining sperm vitality and viability. A moderate freezing rate is generally recommended, although the optimal rate varies across species.

If the cooling rate is too slow, cells lose water to match the osmotic balance with the surrounding solution. This dehydration can cause cell death. Conversely, if the cooling rate is too fast, water does not have enough time to leave the cells, leading to intracellular freezing. The formation of large ice crystals inside the cells is lethal. With a moderate or optimal freezing rate, some water exits the cell and the remaining water either vitrifies (turns into a glass-like state) or forms small, tolerable ice crystals. Rapid thawing prevents these small crystals from recrystallizing, keeping the sperm viable for fertilization. Using cryoprotectants helps increase the rate of vitrification and improves the survival of sperm after thawing (P. C. thomas et al.).

3. Types of Cryopreservation

a) Short-term cryopreservation
b) Long-term cryopreservation

3.1 Short-Term Cryopreservation

The short-term storage of fish sperm is a simple, cost-effective method widely used in fisheries research, ranging from basic studies to applied applications. It plays a key role in understanding and assessing gamete biology and quality, facilitating in vitro fertilization and developing sperm cryopreservation techniques. This approach is employed in selective breeding programs, hatchery production and advanced molecular studies, such as disease detection in commercially important aquaculture species. Additionally, it supports the biological conservation of threatened or endangered fish species (Shazada *et al.,* 2023).

Sturgeon sperm has been preserved using cryopreservation in liquid nitrogen or short-term storage at 1–4°C. These methods aim to establish reliable techniques for conserving endangered sturgeon species and supporting artificial reproduction in sturgeon farming. Cryopreservation involves diluting sperm in buffered extenders (pH 8–8.5) containing intracellular cryoprotectants like dimethyl sulfoxide (DMSO), methanol, or ethylene glycol, and extracellular cryoprotectants such as saccharose or egg yolk. Intracellular cryoprotectant concentrations range from 5% to 20%. Freezing rates tested ranged between 0.5°C and 18.5 °C/min, while thawing rates varied from 15°C to 40°C/min over 5–6 seconds. Post-thaw sperm motility ranged from 8% to 10% and fertilization rates for thawed sperm reached up to 73–94%, although average rates were typically around 20% (Billard *et al.,* 2004).

3.2 Long Term Cryopreservation

3.2.1 Pre Freezing Phase

The success of cryopreservation depends on the quality of the milt, so it is essential to evaluate spermatozoa condition before cryopreservation. Milt should always be collected from ripe brooders using the stripping method, in ice-cold, sterilized cryovials. The collection should be performed in clean, dry and sterile vials and stored immediately on ice (Agarwal, 2011). The collected milt should be in a quiescent state and free from contaminants such as water, mucus, blood and gut exudates. Prior to stripping, the urinary bladder can be gently squeezed to avoid contamination with urine. The stripping method, however, may result in contamination from urine, which can negatively affect milt quality (Rana, 1995). Contaminants like urine, blood and mucus can alter the composition of seminal fluid, compromise sperm motility and reducing post-thaw viability (Billard *et al.,* 1995). Urine contamination, in particular, can lead to lower fertilization rates (Bokor *et al.,* 2007).

To avoid contamination from urine and feces, a catheter can be used for milt collection (Cabrita *et al.,* 1998). Anesthetizing the fish prior to collection has also been shown to be beneficial (Kurokura & Hirano, 1980). Anesthetic agents such as Tricaine methane sulphonate (MS-222) can be used before milt collection (Piironen, 1993). Fish can be anesthetized by immersing them in 2-phenoxyethanol for 2 minutes at a concentration of 0.5 ml/l of water (Perchec *et al.,* 1995). For example, O. mykiss was anesthetized with MS-222 in a 1:10,000 dilution water bath during milt collection, which was done by gently massaging the abdomen (Bozkurt *et al.,* 2005). *C. carpio* brooders were anesthetized with a 1:1000 aqueous solution of 2-phenoxyethanol before handling (Boryshpolets *et al.,* 2009) and *C. carpio* males were anesthetized with 2-phenoxyethanol at a dose of 0.5 ml before milt collection (Cejko *et al.,* 2015).

3.2.2 Extender

Cryopreservation relies heavily on extenders, which are essential for diluting sperm and increasing its volume for artificial breeding. An extender is a medium used to dilute sperm, whereas a cryoprotectant is a substance added to the extended sperm dilution to shield the sperm from temperature-induced shocks and cryotoxicity during freezing (Muchlisin, 2004b). Fish sperm is often highly viscous and, in many species, only small volumes are produced. Extenders play a crucial role in cryopreservation, as they facilitate sperm dilution, induce initial motility and enhance fertilization rates in cryopreserved sperm. Spermatozoa can be preserved for durations ranging from a day to several years, with their motility maintained under low temperatures (Muchlisin, Z. A., 2005).

Ringer's solution and physiological solutions are widely used as practical extenders because they are simple to prepare. A physiological solution typically contains 7.98 g/L NaCl and 0.2 g/L $NaHCO_3$ (Alawi *et al.,* 1995), while Ringer's solution is composed of 7.5 g/L NaCl, 0.2 g/L KCl, 0.2 g/L $CaCl_2$ and 0.2 g/L $NaHCO_3$. Ringer's solution is commonly employed for freshwater fish spermatozoa. For marine fish, a modified Ringer solution containing 13.5 g/L NaCl, 0.6 g/L KCl, 0.25 g/L $CaCl_2$, 0.35 g/L $MgCl_2$ and 0.2 g/L $NaHCO_3$ is used. Variations such as Ringer's solution mixed with milk for tilapia (*Oreochromis niloticus*) spermatozoa and Ringer's solution with honey for milkfish (*Chanos chanos*) and black porgy (*Acanthopagrus schlegeli*) spermatozoa have also been found effective (Chao, 1991).

Muchlisin *et al.* (2004a) reported that a 1:20 dilution ratio of Ringer's solution yielded higher sperm motility in bagrid catfish (*Mystus nemurus*). Other extenders include saline solutions containing 75 mmol/L NaCl, 70 mmol/L KCl, 2 mmol/L $CaCl_2$, 1 mmol/L $MgSO_4$ and 20 mmol/L Tris buffer (pH 8), which are suitable for cyprinid fish spermatozoa (Lahnsteiner *et al.,* 2000a). Additionally, Kurokura-1, a solution comprising 128.4 mM NaCl, 2.7 mM KCl, 1.4 mM $CaCl_2$ and 2.4 mM $NaHCO_3$, is effective for common carp (*Cyprinus carpio*) spermatozoa (Linhart *et al.,* 2000).

3.2.3 Cryoprotectant

Cryoprotectants are low molecular weight compounds that penetrate cells and reduce the freezing points of solutions. When combined with an appropriate dilution ratio, cryoprotectants can enhance the cryo-resistance of spermatozoa. These compounds require time to penetrate cells (a process known as equilibration); however, prolonged exposure before freezing can become toxic to sperm (Cloud & Patton, 2008). While higher concentrations of cryoprotectants can mitigate most cryo-injuries, they may simultaneously pose toxic risks to cells (Tekin *et al.,* 2007). Thus, determining an optimal cryoprotectant concentration is essential for developing an effective cryopreservation protocol. Additionally, the protective effects of cryoprotectants vary across fish species (Yavas *et al.,* 2014).

Cryoprotectants play a crucial role in ensuring the survival of spermatozoa during cryopreservation. They are broadly categorized into two types: permeating and non-permeating (Tiersch *et al.,* 2007). Permeating cryoprotectants, such as dimethyl sulfoxide (DMSO), glycerol, methanol and propanediol, lower the freezing point of the solution, replace intracellular water to minimize osmotic shock and reduce the formation of damaging intracellular ice (Leung, 1991). Non-permeating cryoprotectants include proteins (e.g., milk, egg yolk and bovine serum albumin [BSA]), sugars (e.g., glucose and sucrose) and synthetic polymers (e.g., polyethylene glycol and polyvinylpyrrolidone). These stabilize cellular membranes during cryopreservation (Meryman, 1971). Using an insufficient amount of cryoprotectant before cooling reduces effectiveness, whereas excessive amounts can cause osmotic swelling and cell rupture during thawing and dilution (Taylor *et al.,* 1974). Cryoprotectants are known to prevent ice crystal formation during freezing (Lahnsteiner *et al.,* 2004).

Without cryoprotectants, very few spermatozoa survive due to ice crystal formation at low temperatures, but the same concentrations that protect frozen cells can be lethal to unfrozen cells (Chao, 1991). The effectiveness of cryoprotectants lies in their ability to rapidly penetrate cells during freezing, delaying intracellular freezing and minimizing the effects of the solution (Simione, 1998). Common cryoprotectants used for fish sperm include DMSO, methanol and propylene glycol (PG) (Routray *et al.,* 2008). Propylene glycol has been found to be an effective cryoprotectant for yellowtail flounder (*Pleuronectes ferrugineus*) sperm, though it resulted in only moderately good post-thaw motility in African catfish (*Clarias gariepinus*) (Horvath & Urbanyi, 2000). Methanol at 10% was effective for the cryopreservation of bitterling (*Rhodeus ocellatus*) milt (Ohta *et al.,* 2001) and *C. gariepinus* (Viveiros *et al.,* 2000), while 5% methanol was suitable for tilapia (*Oreochromis niloticus*) milt (Routray *et al.,* 2008). DMSO has demonstrated excellent success in preserving sperm from various freshwater species (Kwantong & Bart, 2006) and is regarded as a universal cryoprotectant (Chao & Liao, 2001).

For *Cirrhinus mrigala*, cryopreservation using glucose as a co-cryoprotectant at 0.5% and egg yolk at 10% provided the highest post-thaw motility duration (Betsy *et al.,* 2015). Similarly, BSA at 2% yielded the best post-thaw motility duration in *Cyprinus carpio* (Betsy & Kumar, 2016).

4. Frezing Phase

A freezing rate that is too high leads to the formation of small ice crystals within cells due to insufficient time for free water to separate from the cytoplasm. These ice crystals can puncture the cell membrane and the membranes of organelles. Conversely, a freezing rate that is too low exposes cells to a concentrated cytoplasm for an extended period, causing a "pickling effect," where high salt concentrations denature biomolecules and alter the pH (Diwan *et al.,* 2010).

In one protocol, sperm straws were frozen on a stainless-steel tray at −80°C for 4 minutes before being immersed in liquid nitrogen (LN_2) (Tiersch *et al.,* 1994). Freezing *Cyprinus carpio* milt at 3 cm above the LN_2 surface for 3 minutes before immersion resulted in high post-thaw motility, fertilization and hatching rates (Horvath *et al.,* 2003). Another method involved placing 0.5 ml straws of *C. carpio* milt horizontally on a styrofoam raft floating 3 cm above LN_2 at −130°C for 20 minutes before immersion, which preserved sperm fertility without adverse effects (Boryshpolets *et al.,* 2009).

The optimal freezing rate for *C. carpio* milt was found to be 5°C/min from 2°C to −7°C and 25°C/min from −7°C to −70°C (Cognie *et al.,* 1989). Alternatively, slower cooling rates of 4°C/min from 0°C to −4°C and 11°C/min from −4°C to −80°C were also effective for cryopreservation (Magyary *et al.,* 1996). A specific cooling program of 4°C/min from 4°C to −9°C, followed by 11°C/min from −9°C to −80°C, with a 6-minute hold at −80°C before immersion in LN_2, achieved high sperm motility (69 ± 14%) and moderate fertilization rates (56 ± 10%) in *C. carpio* (Linhart *et al.,* 2000). For *Clarias gariepinus*, spermatozoa can be frozen by initially cooling at −5°C/min from +5°C to −35°C, followed by cooling to either −50°C or −70°C (Viveiros *et al.,* 2000).

5. Storage Phase

Frozen milt, whether in the form of pellets, vials, or straws, is stored at −196°C in liquid nitrogen within cryocans. At this temperature, spermatozoa can be preserved indefinitely without any deterioration in cell quality (P. C. thomas et al.).

6. Thawing

The rate of thawing is a critical step and a decisive factor in the success of the cryopreservation process. Thawing is essentially the reverse of freezing, but rapid thawing after the cooling process is generally preferred. However, excessively high or low thawing rates can be detrimental to cryopreserved spermatozoa (Diwan *et al.,* 2010). Thawing rates must be fast enough to prevent recrystallization, which is crucial for maintaining the viability of spermatozoa (Lahnsteiner, 2000). An ideal thawing procedure minimizes or eliminates recrystallization and ice crystal formation during the process. The temperature change during thawing should facilitate the movement of water and cryoprotectants while preventing intracellular ice recrystallization (Richardson *et al.,* 2011).

In cyprinid fishes, a fertilization rate of 57% was achieved for *Ctenopharyngodon idella* when thawing was performed quickly in a water bath at 20°C (Durbin *et al.,* 1982). For freshwater carps (*Labeo rohita*, *Cyprinus carpio*, *Puntius gonionotus*, *C. idella*, *Aristichthys nobilis* and *Pangasius sutchi*), milt was thawed by swirling frozen ampoules in tap water at 29°C (Withler, 1982). Similarly, the milt of Indian major carps (IMC) and *Hypophthalmichthys molitrix* was thawed by swirling straws in tap water at 30°C (Kumar, 1988).

For *Tor khudree*, thawing at 37 ± 1°C for 5–10 seconds resulted in a high post-thaw motility of 92–98% and a hatching rate of 25.7% (Basavaraja & Hegde, 2004). In *C. idella*, the highest motility (83.4 ± 2.1%) and fertilization rate (85.6 ± 2.8%) were achieved when milt was thawed at 35°C for 30 seconds (Yavas & Bozkurt, 2011). For *C. carpio*, thawing at 30°C for 30 seconds resulted in a post-thaw motility of 52.6 ± 1.4% (Bozkurt & Yavas, 2017).

In salmonids (*Oncorhynchus mykiss*, *Salmo trutta lacustris*, *S. trutta fario*, and *Salvelinus fontinalis*), the highest fertilization rates were obtained when milt was thawed at 25°C in a water bath for 30 seconds. Deviations of just 5 seconds in thawing time or 5°C in thawing temperature significantly reduced the post-thaw fertilization ability (Lahnsteiner *et al.,* 1996). For *T. khudree*, thawing at 37°C for 40 seconds in a water bath was effective (Ponniah *et al.,* 1999). For *O. mykiss*, the best results were obtained by thawing 0.5 ml and 1.8 ml straws at 25°C for 30 seconds, while 5 ml straws required 60°C for 30 seconds or 80°C for 20 seconds (Cabrita *et al.,* 2001). In another study, *O. mykiss* milt was thawed at 10°C for 30 seconds in a water bath (Scheerer & Thorgaard, 1989). For salmonid fishes, 0.5 ml straws were thawed at 25°C for 30 seconds, while 1.2 ml and 5.0 ml straws were thawed at 30°C for 30 seconds (Lahnsteiner *et al.,* 1997b).

7. Post Thaw Phase and Insemination

During this phase, sperm that have survived cryopreservation are prepared for artificial insemination. It is important to assess sperm motility after thawing, as several factors influence the post-thaw fertility of cryopreserved spermatozoa. Artificial insemination should be performed immediately after thawing, as the motility period of spermatozoa decreases over time following the thawing process. (P. C. thomas et al.).

8. Applications in Aquaculture

This technology offers numerous benefits for the preservation and utilization of milt from brooders of optimal age, enabling its use at any time in the future.

- It helps eliminate inbreeding issues by facilitating the exchange of cryopreserved spermatozoa between hatcheries.
- Spermatozoa can be made available year-round, regardless of breeding season.
- It enables breeding during off-seasons.
- Gamete availability from both sexes can be synchronized, ensuring sperm economy.
- Broodstock management becomes more efficient on farms.
- It supports the production of viable and robust offspring through intra-species hybridization.
- It addresses challenges associated with the short viability of gametes.
- Genetic preservation of desired lines becomes feasible.
- Crossbreeding can be conducted at any time of the year.
- Germplasm storage for genetic selection programs and species conservation is facilitated.
- The technology aids hybridization programs and genetic engineering research in fish.
- It paves the way for advancements such as cryobanking of viable gametes, gene banking and genetic manipulation, similar to practices in animal production (Judith Betsy *et al.,* 2021).

9. Disadvantages

- Cryopreservation of fish embryos is currently unviable due to challenges similar to those faced in preserving fish oocytes, including high sensitivity to chilling and low membrane permeability. However, cryopreserving isolated embryonic cells offers an alternative for preserving both maternal and paternal genomes (Tsai & Lin, 2012).
- A significant drawback of this technique is the potential formation of ice crystals within cells, which can lead to cellular damage.
- The use of inappropriate cryoprotectants can further compromise cell viability.
- Water migration during the process can result in extracellular ice formation and cellular dehydration, both of which can directly harm the cells.

Conclusion

Cryopreservation holds significant potential for advancing aquaculture by enabling the long-term storage and management of aquatic species genetic resources. This technology can enhance breeding programs, preserve endangered species and support the genetic diversity necessary for sustainable aquaculture practices. However, challenges remain, including optimizing cryopreservation protocols for different species and improving the efficiency of sperm and egg preservation techniques. Continued research and technological advancements are essential to fully realize the benefits of cryopreservation in aquaculture, ensuring more resilient, productive and sustainable aquatic farming systems for the future.

References

1. Agarwal, N. K. (2011). Cryopreservation of fish semen. *Himalayan Aquatic Biodiversity Conservation and New Tools in Biotechnology. 1st ed. Transmedia Publication, Uttarakhand*, 104-127.
2. Alawi, H., Nuraini, N. Aryani, and S. Hutapea. 1995. Pengembangbiakan Ikan. Pekanbaru: Fakultas Perikanan Univ. Riau
3. Basavaraja, N., & Hegde, S. N. (2004). Cryopreservation of the endangered mahseer (*Tor khudree*) spermatozoa: I. Effect of extender composition, cryoprotectants, dilution ratio, and storage period on post-thaw viability. *Cryobiology*, *49*(2), 149-156.
4. Betsy, C. J., & Kumar, J. S. S. (2016). Influence of bovine serum albumin (BSA) on the spermatological parameters of *Cyprinus carpio* during cryopreservation. *Journal of Aquaculture in the Tropics*, *31*(1/2), 103.
5. Betsy, C. J., Kumar, J. S. S., & Rajagopalasamy, C. B. T. (2015). Role of glucose in enhancing life and potency of *Cirrhinus mrigala* spermatozoa during cryopreservation. *Journal of Applied and Natural Science*, *7*(1), 159-164.
6. Billard, R., Cosson, J., Noveiri, S. B., & Pourkazemi, M. (2004). Cryopreservation and short-term storage of sturgeon sperm, a review. *Aquaculture*, *236*(1-4), 1-9.
7. Billard, R., Cosson, J., Perchec, G., & Linhart, O. (1995). Biology of sperm and artificial reproduction in carp. *Aquaculture*, *129*(1-4), 95-112.
8. Bokor, Z., Muller, T., Bercsenyi, M., Horvath, L., Urbanyi, B., & Horvath, A. (2007). Cryopreservation of sperm of two European percid species, the pikeperch (*Sander lucioperca*) and the Volga pikeperch (*S. volgensis*). *Acta Biologica Hungarica*, *58*(2), 199-207.
9. Boryshpolets, S., Dzyuba, B., Rodina, M., Li, P., Hulak, M., Gela, D., & Linhart, O. (2009). Freeze-thawing as the factor of spontaneous activation of spermatozoa motility in common carp (*Cyprinus carpio* L.). *Cryobiology*, *59*(3), 291-296.
10. Bozkurt, Y., & Yavas, I. (2017). Effect of extender compositions, glycerol levels, and thawing rates on motility and fertility of cryopreserved wild African Catfish (*Clarias gariepinus*) sperm. *Israeli Journal of Aquaculture-Bamidgeh*, *69*.
11. Bozkurt, Y., Akcay, E., Tekin, N., & Secer, S. (2005). Effect of freezing techniques, extenders and cryoprotectants on the fertilization rate of frozen rainbow trout (*Oncorhynchus mykiss*) sperm. *Israeli Journal of Aquaculture-Bamidgeh*, *57*.

12. Cabrita, E., Alvarez, R., Anel, L., Rana, K. J., & Herraez, M. P. (1998). Sublethal damage during cryopreservation of rainbow trout sperm. *Cryobiology*, *37*(3), 245-253.
13. Cabrita, E., Robles, V., Alvarez, R., & Herraez, M. P. (2001). Cryopreservation of rainbow trout sperm in large volume straws: application to large scale fertilization. *Aquaculture*, *201*(3-4), 301-314.
14. Cejko, B. I., Krejszeff, S., Sarosiek, B., Zarski, D., Judycka, S., & Kowalski, R. K. (2015). Biochemical factors of common carp *Cyprinus carpio* L. 1758, seminal plasma and its relationship with sperm motility parameters. *Journal of Applied Ichthyology*, *31*, 10-17.
15. Chao, N. H., & Liao, I. C. (2001). Cryopreservation of finfish and shellfish gametes and embryos. *Reproductive biotechnology in finfish aquaculture*, 161-189.
16. Chao, N.H. 1991. Fish sperm cryopreservation in Taiwan: Technology advancement and extention efforts. International Symposium on Reproductive Biology in Aquaculture. Taipei: Department of Aquaculture, Taiwan Fisheriesv Research Institute
17. Cloud, J., & Patton, S. (2008). -Basic principles of fish spermatozoa cryopreservation. In *Methods in Reproductive Aquaculture* (pp. 259-272). CRC Press.
18. Cognie, P. F., Billard, R., & Chao, N. H. (1989). La cryoconservation de la laitance de la carpe, *Cyprinus carpio*. *Journal of applied ichthyology*, *5*(4), 165-176.
19. Diwan, A. D., Ayyappan, S., Lal, K. K., & Lakra, W. S. (2010). Cryopreservation of fish gametes and embryos. *The Indian Journal of Animal Sciences*, *80*(4), 109-124.
20. Durbin, H., Durbin, F. J., & Stott, B. (1982). A note on the cryopreservation of grass carp milt. *Aquaculture Research*, *13*(3), 115-117.
21. Horvath, A., & Urbanyi, B. (2000). The effect of cryoprotectants on the motility and fertilizing capacity of cryopreserved African catfish *Clarias gariepinus* (Burchell 1822) sperm. *Aquaculture Research*, *31*(3), 317-324.
22. Horvath, A., Miskolczi, E., & Urbanyi, B. (2003). Cryopreservation of common carp sperm. *Aquatic Living Resources*, *16*(5), 457-460.
23. Judith Betsy, C., Siva, C., & Stephen Sampath Kumar, J. (2021). *Cryopreservation and its application in aquaculture*. Rijeka, Croatia: IntechOpen.
24. Kleeberger, C. A., Lyles, R. H., Margolick, J. B., Rinaldo, C. R., Phair, J. P., & Giorgi, J. V. (1999). Viability and recovery of peripheral blood mononuclear cells cryopreserved for up to 12 years in a multicenter study. *Clinical Diagnostic Laboratory Immunology*, *6*(1), 14-19.
25. Kumar, K. (1988). A comparative study of various extenders for cryopreservation of carp spermatozoa.

26. Kurokura, H., & Hirano, R. (1980). Cryopreservation of rainbow trout sperm. *Nippon Suisan Gakkaishi*, *46*, 1493-1495.
27. Kwantong, S., & Bart, A. N. (2006). Cryopreservation of black ear catfish, *Pangasius larnaudii*,(Bocourt) sperm. *Aquaculture Research*, *37*(9).
28. Lahnsteiner, F. R. A. N. Z. (2000b). Semen cryopreservation in the Salmonidae and in the Northern pike. *Aquaculture Research, 31*(3), 245-258.
29. Lahnsteiner, F., Berger. B., A. Horvath, B. Urbanyi, and T. Weismann. (2000a). Cryopreservation of spermatozoa in cyprinid fishes. Theriogenology 54: 1477-1498
30. Lahnsteiner, F., Mansour, N., & Berger, B. (2004). Seminal plasma proteins prolong the viability of rainbow trout (*Oncorynchus mykiss*) spermatozoa. *Theriogenology*, *62*(5), 801-808.
31. Lahnsteiner, F., Patzner, R. A., & Weismann, T. (1996). Semen cryopreservation of salmonid fishes: influence of handling parameters on the post thaw fertilization rate. *Aquaculture Research*, *27*(9), 659-671.
32. Lahnsteiner, F., Weismann, T., & Patzner, R. A. (1997). Methanol as cryoprotectant and the suitability of 1.2 ml and 5 ml straws for cryopreservation of semen from salmonid fishes. *Aquaculture Research*, *28*(6), 471-479.
33. Leung, L. K. (1991). Principles of biological cryopreservation. In "Fish Evolution and Systematics: Evidence From Spermatozoa" (BG Jamieson, Ed.).
34. Linhart, O., Rodina, M., & Cosson, J. (2000). Cryopreservation of sperm in common carp *Cyprinus carpio*: sperm motility and hatching success of embryos. *Cryobiology*, *41*(3), 241-250.
35. Magyary, I., Urbanyi, B., & Horvath, L. (1996). Cryopreservation of common carp (*Cyprinus carpio* L.) sperm II. Optimal conditions for fertilization. *Journal of Applied Ichthyology*, *12*(2), 117-119.
36. Meryman, H. T. (1971). Cryoprotective agents. *Cryobiology*, *8*(2), 173-183.
37. Muchlisin Z.A. 2004b. Preliminary study on spermatozoa cryopreservation and evaluation of dietary protein on gonadal development of bagrid catfish (*Mystus nemurus*) female Broodstock. Thesis, University Sciences Malaysia, Penang.
38. Muchlisin Z.A., R. Hashim and A. Chong. 2004a. Preliminary study on the cryopreservation of bagrid catfish spermatozoa: Effect of different extenders and cryoprotectants on the motility after short-term storage. *Theriogenology, 62* (1-2): 25-37
39. Muchlisin, Z. A. (2005). Current status of extenders and cryoprotectants on fish spermatozoa cryopreservation. *Biodiversitas Journal of Biological Diversity*, *6*(1).

40. Nazim, N., Manzoor, M., Buhroo, Z. I., Mir, M. R., & Nagoo, S. A. Cryopreservation of Plant and Animal Tissues.
41. Ohta, H., Kawamura, K., Unuma, T., & Takegoshi, Y. (2001). Cryopreservation of the sperm of the Japanese bitterling. *Journal of Fish Biology*, *58*(3), 670-681.
42. P. C. THOMAS *et al.,* Breeding and seed production of FINFISH and SHELL FISH
43. Perchec, G., Jeulin, C., Cosson, J., Andre, F., & Billard, R. (1995). Relationship between sperm ATP content and motility of carp spermatozoa. *Journal of cell science*, *108*(2), 747-753.
44. Piironen, J. (1993). Cryopreservation of sperm from brown trout (*Salmo trutta m. lacustris* L.) and Arctic charr (*Salvelinus alpinus* L.). *Aquaculture*, *116*(2-3), 275-285.
45. Ponniah, A. G., Sahoo, P. K., Dayal, R., & Barat, A. (1999). Cryopreservation of *Tor putitora* spermatozoa: effect of extender composition, activating solution, cryoprotectant and equilibration time.
46. Rana, K. J. (1995). Cryopreservation of fish spermatozoa. *Cryopreservation and Freeze-Drying Protocols*, 151-165.
47. Richardson, G. F., McNiven, M. A., & Mansour, N. (2011). Effect of methanol concentration and thaw rate on the viability and fertility of cryopreserved Arctic char, Salvelinus alpinus (L.), spermatozoa. *Aquaculture Research*, *42*(8), 1096-1100.
48. Routray, P., Dash, S. N., Dash, C., Swain, P., Sarkar, S. K., & Sarangi, N. (2008). Cryopreservation of silver barb *Puntius gonionotus* (Bleeker) spermatozoa: effect of extender composition, cryoprotective agents and freezing rate on their postthawing fertilization ability. *Aquaculture Research*, *39*(15), 1597-1605.
49. Scheerer, P. D., & Thorgaard, G. H. (1989). Improved fertilization by cryopreserved rainbow trout semen treated with theophylline. *The Progressive Fish-Culturist*, *51*(3), 179-182.
50. Shazada, N. E., Alavi, S. M. H., Siddique, M. a. M., Cheng, Y., Zhang, S., Rodina, M., Kocour, M., & Linhart, O. (2023). Short-term storage of sperm in common carp from laboratory research to commercial production—A review. *Reviews in Aquaculture*, *16*(1), 174–189. https://doi.org/10.1111/raq.12827
51. Simione, F. (1998). American Type Culture Collection in cooperation with NALGE Nunc International Corp. *Cryopreservation manual.*
52. Taylor, R., Adams, G. D. J., Boardman, C. F. B., & Wallis, R. G. (1974). Cryoprotection—Permeant vs nonpermeant additives. *Cryobiology*, *11*(5), 430-438.

53. Tekin, N., Secer, S., Akcay, E. R. G. U. N., Bozkurt, Y., & Kayam, S. (2007). Effects of glycerol additions on post-thaw fertility of frozen rainbow trout sperm, with an emphasis on interaction between extender and cryoprotectant. *Journal of Applied Ichthyology*, *23*(1), 60-63.
54. Tiersch, T. R., Goudie, C. A., & Carmichael, G. J. (1994). Cryopreservation of channel catfish sperm: storage in cryoprotectants, fertilization trials, and growth of channel catfish produced with cryopreserved sperm. *Transactions of the American Fisheries Society*, *123*(4), 580-586.
55. Tiersch, T. R., Yang, H., Jenkins, J. A., & Dong, Q. (2007). Sperm cryopreservation in fish and shellfish. *Society of Reproduction and Fertility supplement, 65*, 493.
56. Tsai, S., & Lin, C. (2012). Advantages and applications of cryopreservation in fisheries science. *Brazilian archives of biology and technology*, *55*, 425-434.
57. Viveiros, A. T. M., So, N., & Komen, J. (2000). Sperm cryopreservation of African catfish, *Clarias gariepinus*: cryoprotectants, freezing rates and sperm: egg dilution ratio. *Theriogenology*, *54*(9), 1395-1408.
58. Withler, F. C. (1982). Cryopreservation of spermatozoa of some freshwater fishes cultured in South and Southeast Asia. *Aquaculture*, *26*(3-4), 395-398.
59. Yavas, I., & Bozkurt, Y. (2011). Effect of different thawing rates on motility and fertilizing capacity of cryopreserved grass carp (*Ctenopharyngodon idella*) sperm. *Biotechnology & Biotechnological Equipment*, *25*(1), 2254-2257.
60. Yavas, I., Bozkurt, Y., & Yıldız, C. (2014). Cryopreservation of scaly carp (*Cyprinus carpio*) sperm: effect of different cryoprotectant concentrations on post-thaw motility, fertilization and hatching success of embryos. *Aquaculture international*, *22*, 141-148.

ARTIFICIAL INTELLIGENCE AND THE FUTURE OF ZOOLOGY

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Abstract

Artificial intelligence (AI) stands at the forefront of modern scientific innovation. It has revolutionized our understanding of the world around us and its effects on Zoology also called as animal science have been profound. With continued advancements in AI technology, new opportunities to explore the unknown will continue to arise offering us unprecedented insight into this fascinating field. AI technology offers immense potential for animal scientists to improve their work. Automated tracking and predictive analytics allow data analysis on an unprecedented scale, enabling greater insight into complex biological systems than ever before. This can lead to improved animal welfare through better resource optimization, as well as more informed decision making in conservation efforts. AI also helps to reduce the workload of researchers by automating mundane tasks that would otherwise take a long time to complete. The good news is that it's unlikely that AI will completely replace animal scientists any time soon; however, certain roles within the field may become automated by technology over time. So while it's important to pay attention to advances in AI technology, it's also possible to use them for advantage and secure the place in the workforce of tomorrow. Moreover, this technology continues to evolve, so too will its impact on our lives and careers.

Keywords: Artificial Intelligence, Zoology, Animal Science, Machine Learning.

Inroduction

Artificial Intelligence (AI) is a rapidly evolving field of technology that has become increasingly popular over the past few years. It's often used to refer to machines and computer systems which are capable of making decisions, solving problems and learning from their environment. AI can be further broken down into two main categories namely machine learning and deep learning. Machine learning involves algorithms being fed data in order to recognize patterns and make predictions about future outcomes. Deep learning requires more complex algorithms which are designed for tasks such as natural language processing or predictive analytics. The potential applications of Artificial Intelligence are vast ranging from health care diagnostics to financial services automation. With its ability to analyze massive amounts of data quickly and accurately, AI promises to revolutionize many industries including animal science by automating repetitive processes, improving decision making accuracy and providing personalized recommendations based on user preferences. As this technology continues to evolve, so too will its impact on our lives and careers. Artificial intelligence (AI) stands at the forefront of modern scientific innovation. Its research applications range from medical diagnostics to climate tracking, with the scope of AI research expanding continuously. Of note, AI is making particularly significant strides in zoological research. One challenge of zoological research, a discipline focused on animal classification, behavior, physiology, development, genetics and evolution, disease modeling, and paleozoology, is the management and interpretation of extensive and complex datasets. The rapid emergence of advanced AI techniques, such as machine learning and, in particular, deep learning, as well as the emergence of big data, has marked the beginning of an era of intelligent data-centric zoological research. Although AI has been popular for some time, its incorporation into zoological research has not kept pace with its application in other biological fields. Thus, the question arises as to why AI technologies have not been promptly adopted in animal research. A possible factor for the lack of application may be the inefficiency of computational resources and scarcity of expansive zoological datasets. Additionally, zoologists may lack the foundational knowledge required to understand and implement these approaches, creating uncertainty regarding the selection of models suitable for their objectives. Moreover, the rapid and continuous evolution of complex AI model architectures, like Bidirectional Encoder Representations from Transformers, make it challenging for zoological researchers to stay current. As access to advanced computational tools and comprehensive zoological datasets expands, it may pave the way for broader adoption of these algorithms in mainstream research. Nevertheless, unfamiliarity with these techniques persists among many zoologists, necessitating a foundational understanding of when, why, and how to employ these methods, as well as what type of data is suitable for their application.

History of AI in Zoology

AI was first defined by Stanford Professor John McCarthy in 1955 as a 'the science and engineering of making intelligent machines'. The history of AI in animal science is like a roller coaster ride. From the early days when machine learning algorithms were first used to identify and interpret data from animals, through today's automation technology where robots are being developed that can mimic certain behaviors of animals, it has been an exciting journey. Here's a look at the historical perspective on AI's role in animal science or zoology:

- AI development has enabled scientists to better understand how animals interact with each other and their environment.

- Machine learning models have helped researchers analyze large sets of data quickly and accurately.
- Automation technologies such as robotic arms allow for faster collection of samples and more accurate measurements.
- Artificial neural networks improve predictive analytics by providing insights into behavior patterns within species.
- Natural language processing helps biologists create comprehensive databases of information about different species. AI has revolutionized our understanding of the world around us and its effects on animal science have been profound. With continued advancements in AI technology, new opportunities to explore the unknown will continue to arise offering us unprecedented insight into this fascinating field.

Benefits of AI for Zoology

AI technology offers immense potential for animal scientists to improve their work. Automated tracking and predictive analytics allow data analysis on an unprecedented scale, enabling greater insight into complex biological systems than ever before. This can lead to improved animal welfare through better resource optimization, as well as more informed decision making in conservation efforts. AI also helps to reduce the workload of researchers by automating mundane tasksthat would otherwise take a long time to complete. The use of AI in animal science is becoming increasingly widespread, with applications ranging from early detection of disease in livestock, to the development of autonomous robots that help monitor wildlife populations. By providing real-time insights into animal behavior, AI can be used to inform policy decisions around species protection and habitat management. It’s clear that AI has much to offer the field of animal science potentially revolutionizing how we interact with our environment and making us better stewards of nature.

Potential Risks from Automation

As Artificial Intelligence (AI) technology continues to develop, many people are becoming concerned about the potential risks associated with automation. With machines potentially taking over jobs that were once done by humans, there is no doubt that we should be aware and cautious of the risks involved. The key concerns when it comes to AI are:

- Machine Malfunction: Despite its advanced capabilities, automated systems are still prone to malfunctioning or not working as intended due to programming errors or a lack of data accuracy. This could lead to unintended consequences such as financial losses in certain industries or even physical harm if safety protocols aren’t followed correctly.

- Data Accuracy: Automation relies on data being accurate and up-to-date in order for it to function effectively and make decisions accurately. If there's incorrect information input into the system, then it won't be able to produce reliable results, which can have serious repercussions depending on the industry.
- Technology Failure: Technology is always evolving but at any given point, something could go wrong during an update or upgrade process resulting in widespread disruption and unforeseen consequences for businesses relying heavily on AI technologies for their operations. These are just some of the potential issues related to automation that need to be taken seriously before rushing into implementing new technologies in workplaces and homes without considering all possible outcomes first. It's important for us all to stay vigilant and prepared for any eventuality so that we can minimize risk wherever possible and ensure maximum safety both physically and financially.

Challenges to the Adoption of AI

The potential risks from automation have been discussed, but the challenges to AI adoption remain. In order for animal scientists to retain their jobs in this age of machine learning complexities and technology investments, they must be aware of the ongoing hurdles that impede progress towards a fully automated future. Organizations may be hesitant to invest heavily into AI due to its lack of scalability and stability. Without proper guidance and maintenance, it is difficult for companies to ensure that an AI system can handle all the tasks required by an organization or specific job role. Moreover, certain roles within organizations might not require advanced levels of automation such as those held by animal scientists or zoologists who are experts at observing and understanding animals' behavior and thus could potentially be replaced with cheaper labor instead. AI adoption comes with formidable roadblocks; however, these do not mean that automation cannot benefit animal scientists. By educating themselves on how best to use AI tools in conjunction with human expertise, animal scientists can continue to confidently perform their duties while also taking advantage of new opportunities presented by technological advances.

New Job Opportunities for Zoologists

As technology advances, the question of whether Artificial Intelligence (AI) can replace zoologists or animal scientists remains. But what could this mean for career prospects. Could it lead to job creation or professional opportunities. The answer is a resounding yes! Professional opportunities are indeed available to animal scientists in the world of AI and robotics. With new technologies entering the market every day, there is boundless potential for career advancement and increased job prospects. This opens up exciting possibilities for those looking to expand their knowledge base and create innovative solutions that benefit both animals and humans alike. With so many possible avenues open to them, animal scientists now have unprecedented access to an array of cutting-edge tools that could revolutionize not only their work but also how they approach research into animal welfare. The possibilities are truly limitless when it comes to using AI as a tool to improve our understanding of animals' needs from better diagnosis processes through to improved treatments for various conditions; all with the added bonus of greater efficiency and accuracy than ever before. This presents incredible new opportunities for animal scientists across industries, allowing them to make meaningful contributions on a much larger scale than was previously possible. And with such vast potential, who knows what other innovations may yet be discovered.

Ethical Considerations for AI in Zoology

AI is becoming a more prominent part of our lives and has the potential to replace some aspects of Zoology or Animal Science work. As exciting as this may be, there are ethical considerations that need to be addressed in order to make sure AI is used responsibly in animal science research. In terms of AI ethics, it's important to consider how AI will affect animals and their habitat. Will machine learning algorithms identify behaviors or characteristics that could lead to discrimination against certain species. Also, what sort of regulations should be put into place with regards to using AI in animal science? These are all questions that need to be answered before implementing any type of AIdriven technology within the field of animal science. The use of AI can provide researchers with valuable insights they wouldn't otherwise have access to, but must also be done so ethically. It's important to ensure proper evaluation of the impact on animals when designing new technologies for animal science research. Not only the benefits must be considered, but also potential harms if any arise from its implementation. If done right, the power of Artificial Intelligence can be harnessed for good while protecting both wild animals and those kept in captivity alike.

Government Regulations

The emergence of AI technology has created a need for new government regulations. In the field of Zoology or Animal Science, this means that regulatory compliance must be ensured to protect animals from harm and unethical treatment in research studies or farming practices. As AI systems become increasingly sophisticated, it is important that governments develop legislation specifically tailored to regulate their use. AI specific laws will provide clarity on how data can be used while protecting animal welfare and ensuring ethical standards are adhered to. They should also cover issues such as liability and responsibility if things go wrong with an AI system, as well as outlining any other necessary safeguards. With these laws in place, companies would have greater confidence in investing in AI technologies, leading to more job opportunities for scientists working within the sector. It is clear then that there is a real need for governments across the globe to put appropriate measures into place regarding AI regulation and its application within Zoology or Animal Science. Regulations must not only ensure public safety but promote innovation in order to unlock the true potential of Artificial Intelligence technologies ultimately allowing us all to benefit from them.

Conclusion

Artificial intelligence (AI) is making an impact on the field of Zoology or Animal Science. While AI may not completely replace one's job as an animal scientist in the near future, but there is still a need to be prepared for this potential transition. With the right skills and knowledge, we can remain competitive in a rapidly changing industry. It's important to anticipate these changes and focus on developing new strategies or technologies to stay ahead of the curve. In addition to acquiring technical proficiency, animal scientists must also ensure their research results are free from bias when using AI driven methods. Finally, government incentives such as tax credits or grants could help companies invest more heavily in AI driven Animal Science research. This type of investment would create additional opportunities within the field while ensuring data security remains intact throughout any scientific process involving AI technology. As an animal scientist, it's up to you to keep track of developments related to AI and adjust accordingly so you can continue being successful within your profession well into the future. Conflict of Interest: Authors declare that they have no conflict of interests.

References

1. Leonie, N. B., & Hagenodorff, T. (2021). Animals and AI: The role of animals in AI research and application—An overview and ethical evaluation. *Technology in Society, 67*, 101678.
2. Paulson, O. (2023). *AI and the future of animal science careers.*
3. Zhang, Y., Luo, Z., Sun, Y., Liu, J., & Chen, Z. (2023). From beasts to bytes: Revolutionizing zoological research with artificial intelligence. *Zoological Research, 44*(6), 1115–1131.
4. Wang, H. C., Fu, T. F., & Du, Y. Q. (2023). Scientific discovery in the age of artificial intelligence. *Nature, 620*(7972), 47–60.
5. Moor, M., Banerjee, O., & Abad, Z. S. H. (2023). Foundation models for generalist medical artificial intelligence. *Nature, 616*(7956), 259–265.
6. Romero-Ferrero, F., Bergomi, M. G., & Hinz, R. C. (2019). AI: Tracking all individuals in small or large collectives of unmarked animals. *Nature Methods, 16*(2), 179–182.

7. Jordan, M. I., & Mitchell, T. M. (2015). Machine learning: Trends, perspectives, and prospects. *Science, 349*(6245), 255–260.
8. Hinton, G. E., Osindero, S., & Teh, Y. W. (2006). A fast learning algorithm for deep belief nets. *Neural Computation, 18*(7), 1527–1554.
9. Devlin, J., Chang, M. W., & Lee, K. (2019). BERT: Pretraining of deep bidirectional transformers for language understanding. In *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies* (pp. 4171–4186). Minneapolis, MN: Association for Computational Linguistics.
10. Shabbir, J., & Anwer, T. (2018). Artificial intelligence and its role in near future. *arXiv*. https://doi.org/10.48550/arXiv.1804.01396

LAC CULTIVATION:
A GOLDEN RESIN FOR RURAL PROSPERITY

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Abstract

Lac resin is a natural, biodegradable and non-toxic substance making it suitable for use in food, textile, pharmaceutical and other industries. With the growing global preference for eco-friendly and safe materials for human use and consumption, the demand for lac has increased significantly. Lac cultivation also serves as an important source of income for tribal and economically weaker communities living in forest and sub-forest regions of India. India is the predominant producer of lac, contributing over 50% of global production. India produces approximately 20,000 metric tones of raw lac annually and lac culture plays a significant role in earning foreign exchange. The leading lac-producing states are Jharkhand (57%), Chattisgarh (23%) and West Bengal (12%). Nearly three million tribal people in these regions depend on lac cultivation for livelihood. It provides an important source of income and livelihood for these communities, helping to improve their economic conditions. All the primary lac host plants are found in natural woods, along roadsides adjacent to agricultural land and near to villages. Lac cultivation is an important forest-based livelihood activity, where host trees such as Kusum, Palash and Ber, occur abundantly. Lac is a natural resin secreted by *Kerria Lacca* is cultivated mainly on Kusum, Palash and Ber trees. India accounts for 50-60% of global lac production, supporting 3-4 million tribal and forest-depenent families. Lac processing generates high-demand products such as resin, dye and wax used in pharmaceuticals, cosmetics, food industries, paints, electronics and eco-friendly coatings.

Lac insects are exploited for their commercial goods, which include resin, wax and color. Lac cultivation not only provides a living for millions of lac growers, but it also aids in the conservation of enormous swaths of forest and biodiversity linked with the lac insect complex. Promoting and nurturing lac culture would not only slow environmental degradation but will also preserve adjacent flora and wildlife for future generation.

Keywords: Lac Cultivation, *Kerria Lacca*, Natural and Eco-Friendly Properties, Biodiversity Conservation.

Introduction

The term “Lac” originates from the Sanskrit word “Laksha” meaning one hundred thousands, which refers to the large number of insect larvae that densely cover the branches of host plants during the brood development phase (Sharma *et al.,* 2020). In an agricultural country like India, along with the cultivation of crops, insect are also cultivated. Beekeeping, silkworm rearing and lac insects are cultivated under the cultivation of these insects. In trade and industry, lac is a general term used for all types of natural resin secreted by tiny lac insects on specific host trees, predominantly found in India, Thailand, China and Indonesia. In India *Kerria lacca* (Kerr) is the main species responsible for secreting natural resin, (Yogi *et al.,* 2015). These insects flourish on the tender twings of selected host plants such as Palash (*Butea monosperma*), Ber (*Ziziphus mauritiana*), Kusum (*Schleichera oleosa*), Ficus species (*Flemingia semialata*) and others, (Sharma *et al.,* 2010). *Schleichera oleosa, Ziziphus mauritiana and butea monosperma* are the major lac host species. *S. oleosa* is most suitable for kusumi lac, while B. monosperma supports high-quality Rangeeni lac production, Z. mauritiana is suitable for both species but only during specific seasons (Varshney and Teotia, 1967). Each lac strain produces two crops annually.

The lac insect was first studied in 1709 by Father Tuchard in 1782, Kerr named the species, *Coccus lacca*. Later, Chatterjee referred to the lac insect as *Tachardia lacca or Kerria lacca.* Among the six known genera of lac insects, five are capable of secreting lac, but only one, *Laccifer* produces lac in quantities sufficient for commercial recovery. The most common and widely distributed species in India is *Laccifer lacca* (Kerr), which contributes the majority of the commercial lac produced in the country. Until around 1950, India enjoyed a monopoly in the global lac market, producing nearly 85% of the world’s sticklac. After 1950, Thailand emerged as a major competitor. Other countries that produce lac include regions in Africa, Australia, Brazil, Myanmar, Sri Lanka, China, France, Japan and West Germany. In India, the principal lac-producing regions include Assam, Bengal, Bihar, Delhi, Gujrat, Hyderabad, Kashmir, Madhya Pradesh, Chennai, Coimbatore, Mysore, Rajasthan and Uttar Pradesh. More than 90% of India’s lac production comes from Bihar, Jharkhand, West Bengal, Madhya Pradesh, Chhatisgarh, Eastern Maharashtra and Northern Odisha. Additionally smaller pockets of lac cultivation can be found in Andhra Pradesh, Punjab, Rajasthan, Mysore, Gujrat and in the Mirzapur and Sonebhadra districts of Uttar Pradesh.

Almost all the scale insects are harmful as they suck the sap from the plants. Few of them are also beneficial and lac-insect is one among them. Lac is a resinous protective secretion from the lac insect. Lac is a complex substance and it also contain sugar, water and other alkaline substances along with large amounts of resins. The percentages of various constituents are as follows. Resin is 68-90%, Dye 2-10%, Wax is 6%, Albuminous matter 5-10%, mineral matter is 3-7% and water 3%. So, this lac secretion has great commercial value. Due to this purpose, lac insects are cultivated and lac is collected from the host plants. Hence, the lac culture is the commercial production of lac which include regular pruning of the host plants, propagation of lac insects and the processing of the lac. Lac is the gift of nature to mankind and is the only known commercial resin of animal origin. It is the hardened resin secreted by tiny lac insects belonging to a bud family (Zhang, 1993). To produce 1kg of lac resin, around 300,000 insects lose their life. The lac insects yield resin, lac dye and lac wax. Lac still finds extensive use in Ayurveda and Siddha systems of medicine. Lac has the unique properties of being eco-friendly, biodegradable and self-sustainable. Moreover, it is natural material and thus currently it has assumed special importance. Since lac insects are cultured on host trees, which are growing primarily in waste-land areas, promotion of lac and its culture can help in eco-system development with reasonably high economic returns, (Sharma and Ramani, 2010). It also acts as a source of livelihood for tribal and poor sub-forest areas.

Lac insects belong to the Class Insecta, Order Hemiptera, Suborder Homoptera, Superfamily Coccoidea, Family Lacciferadae, Genus Laccifer and Species Lacca. The lac insect is hemimetabolous, meaning it undergoes gradual metamorphosis. It has three life stages, Egg, Nymph (Young one) and Adult. Nymph resemble adult in structure except for their smaller size and undeveloped reproductive organs. Ault males and females differ significantly; the female is almost three times larger than the male. Male lac insects are pinkish-red and may be winge or wingless. They mostly appear during the dry season and survive only 3-4 days, dying soon after mating. Their main features include, A large head with prominent but nonfunctional mouthparts. They bear two pairs of ocelli and seven-segmented abdomen, broad in front and narrow at the end. The last abdominal segment carries a pointed penis and a rounded abdomen with a dorsal spine. Lac insects live inside small cavities formed by the resin (lac) they secrete on their host plants. A female lays 200-500 eggs, all of which contain fully developed embryos, meaning the insect is ovoviviparous. Female lac insects are pink with a flat ventral side and a convex dorsal side. Their distinctive features include, highly reduced eyes, wings and legs. Small vestigial antennae with 3-4 segments. Piercing-sucking mouth parts, the rostrum has two segments. A mesothoracic appendage bearing spiracles (Misra, 1931).

The life cycle of lac insects mainly depends on the ecological factors of the region like the temperature, humidity and the host plant species. It includes four stages namely Eggs, Nymph instars, Pupa and Adult. The egg reached the adult stage within six months. Lac insects are Ovoviviparous types. The females get attached to the host plant inside the resinous mass. The male insect comes out of it's resinous mass by pushing the operculum of the anal opening and then walks over the resinous covering of the female. This walking fertilizes the female within. One male lac insect is capable of fertilizing many females.

After the fertilization, the female grows rapidly until it begins to lay eggs. By the time female starts to lay the eggs, its body contracts on the ventral side and gradually vacating the place for the eggs to be accommodated inside the resin cell. After laying the eggs, the female secretes the lac resin at a faster rate. After about 14 weeks, female completes shrinks in size allowing the light to pass into the cell and onto the eggs. At this stages, two yellow spots appear at the rear end of the resin cell. These spots gradually enlarge and turn orange in colour. This indicates the completion of egg-laying by the female lac insect. After laying the eggs, the female lac insect dies. Now the resin cell with eggs is called as ovisac. The ovisac appears orange in color due to the crimson fluid called the lac dye. This indicates that eggs are about to hatch in a week.

Eggs: After six weeks, the eggs are hatched into first instar larvae called crawlers. These larvae emerge us in very huge numbers and this emergence is termed as swarming. The first instar larva is broad, red-coloured and boat-shaped. It has paired antennae, ocelli and sucking type of mouth parts with proboscis. These larvae prefer succulent shoots as their host. The settled larvae suck the sap from the host and start to secrete resinous substance all over their body.

Pupa: As the resinous secretions come in contact with the air, it becomes hard and forms a coating is called cell. Within the cell various life processes like the growth of larva and morphological changes takes place. Inside the cell, the larvae undergo three moults. After the first moult, both the female and male nymphs lose their appendages, eye become degenerate. The female once inside the cell will never move on the other hand the male comes out through the operculum of the anal opening.

Adult: After about 6-8 weeks the stationary life of larva metamorphoses into adults having cast-off the second and the third moults. Only the male undergoes complete metamorphosis, it loses its proboscis, develops antennae, legs and a pair of wings. The female unergo incomplete metamorphosis. They retain her mouth parts but fail to develop any wings, eyes or appendages.

Female becomes an immobile organism with little resemblance to an insect. They become little more than egg producing organisms. The sex can be determined even during the early stages of development. As in case of males the growth is more in vertical axis. The life span of the female is longer than that of the males. Most of the lac is secreted by the females. The life cycle occurs twice in one year on the same plant. The eggs hatch within a few hours, releasing tiny crimson-re instar lymph called crawlers. These nymphs have two compound eyes, three pairs of legs, a pair of antennae and six anal setae. Their crawlers move over branches until they find suitable twings neither too soft nor too hard and settle in densecluster of 200-300 insects per inch. They insert their needle-like proboscis into the bark to feed on sap. Within a day of setting, the nymphs start secreting semi-solid resin from glands beneath their cuticle. This resin hardens on exposure to air, firming the protective lac covering.

Inside their cells, nymph unergo three moults, the duration of each depending on temperature, humidity and host plants. After the first moult, both male and female nymphs lose their legs, antennae and eyes which become reduced; however, the anal setae increase to ten. The male cell becomes slipper-shaped with a rear operculum, where as the female cell becomes globular. During the second moulting stage, male nymphs pass through prepupal and pupal phases and regenerate their appendages, while females remain degenerate but continue feeding, growing an secreting resin. After the third moult, adult males emerge winged or wingless. They reach maturity much faster than females and cannot feed because their mouthparts are atrophied. They mate with as many females as possible and die shortly afterward. Female remains inside their cells, grow rapidly and deposit most of the lac. As they mature, they become globular and fill the entire cell. Before laying eggs, they shrink to create space for the ovisac, where eggs are deposited. Two yellow spots appear at the cell's rear end, turning orange when the ovisac is full and the eggs are close to hatching within a week, (Lit Jr., 2002). At this stage, the brood lac sticks are cut and used for inoculating new host trees.

Major important host trees are Palas (*Butea monosperma*), Ber (*Zizyphus mauritiana*), Kusum (*Shorea oleosa*), Kher (*Acacica catechu*), Arhar (*Cajanus cajan*), Akash mani (*Acacica auriculiformis*), Ghont (*Zizyphysxylopyra*), Ficus species, Grewea species and Babul (*Acacia Arabica*).

Results

One established lac processing unit has a capacity to process 100 kg of scrap lac in one day. At least four labours are required for lac processing work. Activities like crushing, grading and winnowing work is done due to which in each processing unit, processing of 70 kg. of raw lac can be processed in 8 hours. During this activity first of all lac is crushed in the lac crushing machine approximately 8 to 10 holes in a inch. After crushing this lac is placed in washing machine in which 4.25 kg. of caustic soda mixed with per kilogram lac & washed with water. After washing one-inch-thick layer of lac is spread on solid floor for drying, the place should be shaded and full of air will less sunlight. Drying of lac can be done approximately in a day. When the lac is completely dried then this lac is placed in Osai machine, in which the unwanted material is removed and then it is placed in lac grader in which three types of filters 8 mash, 10 mash and 12 mash is present through which lac grading can be done. After grading seed lac is received as final product. By this method 600-700 gm of seed lac can be received from one kilogram of scrap lac. Villager also gets employment by such kind of processing work.

Lac culture is fairly a simple process and considering the labor required for it, the yield is fairly remunerative to the cultivators. But to get a fair return cultivation should be made in a systematic and scientific method, (Mishra and Pandey, 2021). Very often the cultivators are deprived of a good crop due to lack of knowledge in the cultivation of lac.

The main cultural operations involved in the cultivation of lac are: 1) Pruning of host plant, 2) Brood lac Inoculation, 3) Phunki removal, 4) Insect pest management, 5) Harvesting and 6) Scrapping lac cultivation is done by putting brood lac on suitably prepared specific host plants. The brood lac contains gravid females which are about to lay eggs to give birth to young larvae. After emergence from mother cells, the young larvae settle on fresh twings of host plants, suck the plant sap and grow to form encrustations.

1. Pruning: Pruning lac cultivation is simple, does not need any large investment and requires only part-time attention. In rural area lac cultivation is carried out very casually and the farmers are getting satisfied with very limited production. Usually the host plants like Palash, Kusum and Ber trees are mature for the production of lac at an age of eight to ten years and the farmers are not very serious for pruning the host plants. Due to the defective local practice, host trees loss the vigour and unable to throw out new succulent shoots and in course of time, the trees become weak and die. Proper pruning is extremely important as it helps in growth of new and short shoots suitable for settlement of lac insects. Old and hard branches can never give a satisfactory production. The following points should be borne in mind during the pruning.

- The general health and strength of the tree should be maintained by avoiding excessive pruning.
- Cutting shoul be done in such a way as would keep a good shape of the tree and allow plenty of room for the growth of new shoots.
- Ordinarily, branches exceeding 2 in diameter should be cut close to the branches or trunk from which they arise.

- Dead and discard branches should be removed and split or broken branches should be cut below the split or break.

2. Brood Lac Inoculation: The method by which the lac insects are introduced on to a lac host is known as inoculation. Inoculation should be done on tees which are prepared for lac culture by pruning in due time. This is done by inoculation of newly hatched (Brood) lac nymph. The quantity of brood lac required for a tree depends upon the kind of tree and the size and number of suitable branches. It is estimated that 20 gm brood lac require for 1m of shoot length. In inoculation, the twigs of brood lac are cut in size 12-15 cm in length. Then, the cut pieces of brood twig are to be put in to 60 mesh nylon net bags and tied to fresh tree twigs in such a way that each stick touches the tender branches of trees at several places. The nymphs swarm from brood and migrate to tender and succulent twigs and infest them.

At the time of inoculation following points should be keep in mind for better lac production.

- The brood must be fully mature and free from insect and disease infestation.
- Lac brood should not be kept for long time after harvesting it should be inoculated immediately after crop cutting.
- Lac larvae emerge from the brood within a week or ten days from the time of first emergence and to get best result inoculation should not be delayed beyond 2-3 days of noting larval emergence from the brood lac.
- Before tying of the brood-lac stick should be put into nylon net bags of 60 mes.
- Brood should be tied on upper surface of branches. This will prevent falling of twigs and provide full contact for quick and easy crawling of the nymphs. One should keep a watch on the brood lac dropping down. Ordinarily a well-covered healthy brood lac stick gives adequate larval settlement over 15 to 20 times its length, on the twigs of the tree to be infected so that overcrowding could not be occur. Brood lac from a particular host used year after year is likely to deteriorate in quality. Therefore, alternation of brood and host give production of a better quality of brood lac.

3. Phunki Removal: The brood lac sticks after emergence and settlement of nymph on new branches, the stick with dead lac cells and present resin is called Phunki. This phunki must be removed after full settlement of nymphs at three weeks of inoculation. Small dauli or phunki removal hook can be used for this purpose. After collection of phunki stick should be scraped and sold timely. This practice prevents lac predator and parasite infestation on new crop.

4. Insect- Pest Management: Lac insect is seriously threatened by so many insect pest in all lac growing regions. These insect pest damages about 30-40% of lac population. Three most important insect predator are damages lac population. Three most important insect predator are damages lac population Viz. *Eublemma amabilis Moori*, *Pseudohypatropa pulverca meyr* and *Chrysopearla* spp. Commonly known as lace wing bug, order Neuroptera. These insect pests lay their eggs in lac cells and their grubs feed internally on lac insects within the cells.

Only healthy pest-free brood lac should be used for inoculation. The twigs for inoculation should be cut just before swarming to get healthy brood. The inoculation stick or phunki lac should be removed timely and fumigated or immersed in water to kill the pest. Stick lac should be processed immediately to convert into seed lac. Infected stick lac should be treated with fumigant insecticide along with predators and pest. Regular monitoring is necessary for observation of any deformity of attack of insect pest.

5. Harvesting of Lac: Harvsting is the process of collection of lac from host trees.

Two type of harvesting process is used in most of the regions.

A) Ari Lac harvesting

B) Mature harvesting.

It is one by cutting the lac encrusted twigs when is crop is mature. Immature harvesting and collection of lac before swarming is known as “Ari Lac”. In mature harvesting lac is collected after swarming. The lac obtained is known as mature lac. Mature lac harvesting is of two types in practice as:

- **Partial Harvesting:** This harvesting is performed when surplus brood lac is on the tree and sufficient branches are available on the tree for next generation.
- **Complete Harvesting:** In this process lac is fully harvested from the plant and plant is pruned and left for new shoot emergence.

6. Scrapping: Removal of lac resin incrustation from lac host stick is called scrapping. After harvesting of matured lac and some-time immature lac is need to be scraped as primary processing for long-time storage. This practice is done with the help of scraping knife. With the blade or knife, the harvester carefully scrapes the encrusted resin from the selected branches. The blade is held at a specific angle to ensure efficient removal of the sticklac without damaging the host tree.

7. Collection and Storage: As the sticklac is scraped off, it falls into the collecting container. The harvested sticklac is then transferred to a storage area for further processing. After the sticklac is harvested using any of the above technique, it undergoes further processing, which includes cleaning, grinding, extraction, refining, drying, packaging and storage. These additional steps help remove impurities and the quality of the final product. After harvesting, the raw lac resin is processed to obtain purified lac or shellac. The processing involve cleaning, melting and filtering of the raw lac to remove impurities, twigs and other foreign materials. The purified lac resin is further shaped into thin flakes or blocks, which can be dissolved in alcohol to produce shellac. Processing lac resin also known as sticklac, is a crucial step in lac cultivation. The harvested sticklac undergoes several processing stages to obtain purified lac or shellac, which has various industrial and commercial applications.

A) Cleaning: The first step in processing sticklac is cleaning to remove any impurities, such as bark, leaves, insect debris and dirt that may be present. This is typically one by sieving or winnowing the harvested sticklac to separate the resinous material from the non-resinous particles. The cleaned sticklac is then ready for further processing.

B) Grinding: In the grinding stage, the sticklac is crushed or ground to breakdown the resinous material into smaller particles. This can be done manually using mortar and pestle or by mechanical means such as grinding mills. Grinding increases the surface area of the resin, facilitating the subsequent extraction process.

C) Extraction: The extraction process involves separating the resin from other components of the sticklac such as woody debris, bark and insect parts. These are different methods for resin extraction, including hot water extraction and solvent extraction. The chosen method depends on the desired quality of the final product and the specific requirements of the industry.

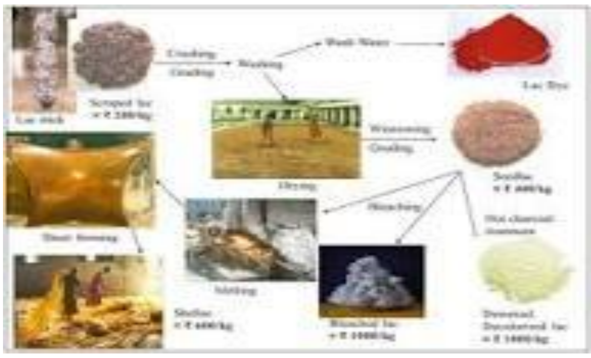
Hot Water Extraction: In this method, the ground sticklac is soaked in hot water. The resin dissolves in the water, while the non-resinous impurities settle down. The resin-rich liquid is then separated from the sediment through filtration or decantation. The collected resinous solution is further processed to remove excess water and impurities.

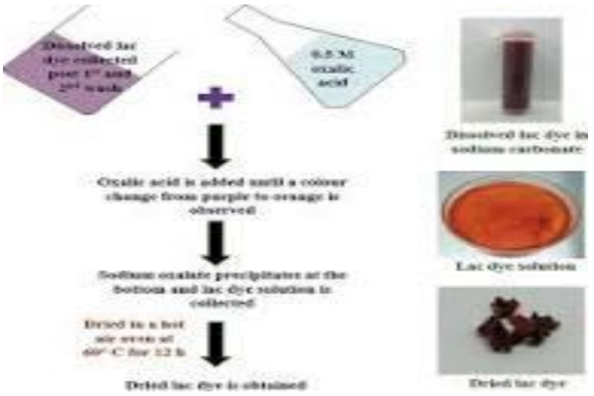
Solvent Extraction: Solvent extraction involves dissolving the resin in a suitable organic solvent, such as ethyl alcohol or methyl ethyl ketone. The resinous solution is then separated from the insoluble impurities by filtration on centrifugation. The solvent is subsequently evaporated to obtain the purified resin.

D) Refining: Refining is an essential step to further purify the extracted resin and remove any remaining impurities. The refined resin has improved quality and is suitable for various applications. Refining techniques may include filtration, centrifugation or sedimentation to separate fine particles or suspended matter from the resinous solution. The refined resin is then collected for drying.

E) Drying: Drying is performed to remove excess moisture from the refined resin. The resin is spread out in thin layers or poured into molds to allow evaporation of moisture. Drying can be done naturally by exposing the resin to sunlight or through artificial drying methods using heat or dehumidification. Proper drying helps prevent the growth of molds and ensures the stability and shelf life of the final product.

F) Packaging and Storage: Once the lac resin is thoroughly dried, it is ready for packaging. The resin is typically packed in airtight containers or bags to protect it from moisture, dust and other contaminants. Proper labeling and storage in a cool, dry place are essential to maintain the quality of the resin during transportation and storage. The quality of the final product depends on the efficiency of the processing steps and the adherence to quality control measures throughout the processing stage.





Discussion

Insects provide useful services to mankind and the environment in a number of ways. They produce useful substances such as honey, wax, dye, shellac, lacquer and silk. Honeybees, Silkworm, Moths, Indian lac insects and Cochineal insects etc. are the best example of semi-domesticated insects, breed by man for the sake of different commercial products obtained from them.

Lac is one of the most valuable natural gifts to man, secreted by a tiny insect, *Laccifer lacca*. It is an exclusive material, which is the only animal origin resin (Jaiswal, 2015). Indian lac insects live on different species of trees in South East Asia. The English word lac derived from the Sanskrit word Laksh, meaning a lakh or hundred thousand. Lac is the hardened resin secreted by tiny lac insects belonging to a bug family. To produce 1 kg of lac resin, approximately 300,000 insects are killed. The lac insects yield resin, lac dye and lac wax etc., still find extensive use in

Ayurveda and Siddha systems of livelihood of poor an tribal people inhabiting forest and sub-forest areas.

Lac insects grow on twigs of certain host plant species, feeds on the plant sap and secrete lac resin from their bodies. Althrough lac insect is a natural pest on host plant but they are not considered as pest because they prouces a useful product. Although there are numerous host plants of lac insect but *Butea monosperma* (Palash), *Zizyphus* Spp (Ber), *Schleichera oleosa* (Kusum) and *Acacia catechu* (Khair) are major host plants. The market demand of Kusumi lac is more and have higher price in market. The Ber trees, Siris (*Albizzia* sp.), *Prosopis Juliflora* are identified as good host for Kusumi brood lac. Some other common host plants in India are *Acacia arabica* (Babool), *Acacia auriculiformis* (Akashmani), *Zizyphus xylopyrus* (M.P. & U.P.), *Shorea talura* (Mysore), *Cajanus cajan* (Pigeon-pea or Arhar), *Grewia leliafolia* (Assam), *Albizzia lebbek* (Siris), *Flemingia macrophylla* (Bholia), *Ficus benghalensis* (Bargad), *Ficus religiosa* (Peepal) etc. (Roonwal *et al.,* 1958).

Lac has been using for the welfare of human beings from the great golden days, no doubt the development of many synthetic products has made its importance to a little lesser degree, but still it can be included in the list of necessary articles. 1. Lac is not soluble in water but is readily soluble in alcohol. This property is used for insulation of electrical connections. 2. Lac fuses easily on heating. 3. It has adhesive property. 4. When mixed with alcohol it exhibits binding properties. 5. It is also soluble in weak alkali like ammonia. 6. It is a bad conductor of heat and thus finds use in electrical appliances.

Lac Products

A) Lac dye: Lac dye is a mixture of anthroquinoid derivatives.m The following are the uses of dye. It is traditionally used to colour wool and silk. It's colour varies between purple red, brown and orange often depending upon the mordant used. It is also used in food and beverages industry for colouring. In recent past, Lac dye has been replaced by synthetic dye, But now-a-days with increasing stress and awareness on use of eco-friendly and safe material, there is a great demand of Lac dye as a colouring material.

B) Lac wax: Lac wax is a mixture of higher alcohol, acids and their esters. It is used in polishes applied on shoes, floor, automobiles etc. It is used in lipstick, crayons, food and drug tablet finishing.

C) Shellac: Shellac is a natural gum resin. It is natural nontoxic, physiologically harmless and edible resin. The following are the important uses of shellac. It is used in fruit coatings e.g. for citrus fruits and apples, parting and glazing agents for sweets, marzipan, chocolate etc. Also used as binder for foodstuff stamp inks e.g. for cheese and eggs. It is used as binder for mascara, nail varnish, additive conditioning shampoo, film forming agent for hair spray, micro-encapsulation for perfumes. It is used for enteric coatings for tablets and as odour barrier. It is used in manufacturing photographic material, lithographic ink and for stiffening felt and hat material. It is utilized in preparation of gramophone records. Lac is use in jewelers and goldsmiths use lac as a filling material in the hollows in ornaments. It is also used in preparation of toys, buttons, pottery and artificial leather. It is also used commonly as sealing wax. With increasing environmental awareness of consumers, this natural and renewable raw material is being used in the development of new products like, Leather, Printing inks (As binder for flexographic printing inks for non-toxic printing of food packaging), Wood treatment (Primers, Polishes, Matt finishes), Electrical (Insulation, capping lamination), Abrasives (Binder for grinding wheels).

Bleached shellac is widely used in the following industry

Chemical Industry

- Paints (as primer for plastic parts and plastic film).
- Aluminium industry: (as primer for aluminium and Aluminium foils).
- Flexographic printing inks.
- Pharmaceuticals (for coating of pills, tables and gel caps and coating for controlled release preparation).
- Confectionery (in coating of confections, chewing gums, marzipan chocolates, nutties, jelly and coffee-beans etc).
- Barrier coating for processed food, vegetables, fruits and dry flowers.
- Cosmetics (used in hairspray, hair and lacquers, hair shampoos and binder for mascara).
- Antique frames for paintings and wood polish (French polish).
- Electrically as binder for lamp cements.
- Electronically it is binder for insulation materials, serves as additive to moulding compounds. Mass coating for print-plates and is adhesive for si-cells.
- Grinding wheels (It is binder for additive of grinding wheels).
- Plastic (It is primer for plastic parts and films).
- Rubber (It is additive to natural rubber).

Lac is applied over the skin in skin diseases. It stops bleeding in wounds and injuries, heals skin ulcers, speeds up recovery process of ulcer, wounds another skin diseases. Purified lac is used in Ayurvedic and Unani medicines. However, sourced as an animal origin, it has a great significance in management of joint disorders Osteoporosis, Osteomalacia, Osteoarthritis etc. It is also helpful in Obesity, Renal and Spleen disorders, Jaundice, Backache problems, Leprosy, Ulceration, Epilepsy and Chicken Pox. It is an amazing liver tonic when taken with other liver stimulant herbs.

Lac culture also known as lac cultivation or lac farming, refers to the production of lac resin, which is a natural secretion produced by certain insects, particularly the lac insect (Kerria lacca), (Mishra, 2000). The economic importance of lac culture is significant and can be attributed to several factors. Lac culture is often practical by small-scale farmers and marginalized communities in rural areas. It provides an important source of income and livelihood for these communities, helping to improve their economic conditions, (Roy and Sharma, 2010). Lac cultivation creates employment opportunities for a large number of people, particularly in rural and agricultural areas. The process involves various stages such as collection, processing and marketing, which requires a significant workforce. Lac resin is used in various industries, primarily for the production of shellac, (Srinivasan, 1956), which is a versatile natural material with a wide range of applications. Shellac is utilized in the production of varnishes, adhesives, coating and polishes for products like furniture, musical instruments, foods and pharmaceuticals. The scale of lac resin and shellac generates substantial revenue for producers and manufacturers. Many lac-producing countries export lac resin and shellac to international markets. The demand for shellac is various industries around the world contributes to foreign exchange earnings and improves trade balances. The processing of lac resin into shellac involves several value-added processes such as purification, grading and refining. These processes create opportunities for additional revenue generation and specialized skills development. In some cultures, artisans use lac and shellac for traditional crafts, such as making jewelry, toys, bangles and decorative items. This preserves cultural heritage and traditional craftsmanship while also providing economic opportunities. Lac cultivation is an important source of income and has high potential for generating employment for both men and women in forest and sub-forest areas of the India, (Kumar, 2002). It is a very remunerative crop, paying high economic returns to the farmer's especially tribal area as well as forest of the country. Traditionally, lac collection was carried out in historical time by tribal communities living in forests. However, with the advancement of scientific lac cultivation techniques, these communities have embraced cultivation practices, leading to significant improvements in their livelihoods, socio-economic conditions, and cultural aspects. As per research, lac cultivation now provides three times more income than traditional agricultural crops. Lac cultivation contributes to rural income, generate employment and can be integrated with agriculture for increased productivity. (Ghosh and Pal, 2019), explored the ecological benefits of lac cultivation, identifying its role in biodiversity conservation. The study demonstrated that lac cultivation supports agroforestry practices, enhances soil fertility and contributes to carbon sequestration, (Sharma, 2006). Furthermore, it highlighted the symbiotic relationship between lac insects and host trees, which strengthens forest ecosystem. Tiwari (2018) explored lac cultivation as an alternative livelihood strategy emphasizing it's potential in reducing economic vulnerability among tribal farmers. The research documented the shift from traditional sub-sistence farming to lac cultivation, leading to increased household incomes and reduced dependence on seasonal employment.

Lac cultivation is relatively environmentally friendly and sustainable. It doesn't require extensive chemical inputs and can be integrated into agroforestry systems, contributing to biodiversity conservation and ecosystem health. For farmers, with diverse land use practices, lac culture can provide an additional income stream alongside other agricultural activity. As the demand for natural an eco-friendly product increases, lac resin and shellac fin applications in the production of bio-based and sustainable materials, further enhancing their economic importance. Overall, lac culture plays a crucial role in the economic development of rural areas, provides employment opportunities, generates revenue and contributes to sustainable agriculture and local economics.

References

1. Jaiswal, A. K. (2015). *Butea monosperma*. Ranchi, Jharkhand: Indian Institute of Natural Gum and Resins (IINGR).
2. Kumar, K. K. (2002). Scope of lac cultivation in employment and income generation. In K. K. Kumar, R. Ramani, & K. K. Sharma (Eds.), *Recent advances in lac culture* (pp. 254–262). ILRI.
3. Lit, I. L., Jr. (2002b). Wax and resin-exuding, cuticular pores and ducts of adult female lac insects (Hemiptera: Coccoidea: Kerriidae). *Philippine Agricultural Scientist, 85*, 122–136.
4. Misra, A. B. (1931). On the anatomy of the larva of *Laccifer lacca*, Kerr (Hemiptera: Coccidae). *Bulletin of Entomological Research, 21*, 161–164.
5. Mishra, Y. D., Sushil, S. N., Kumar, S., & Bhattacharya, A. (2000). Variability of lac productivity and related attributes of *Kerria* spp. (Homoptera: Tachardidae) on ber (*Ziziphus mauritiana*). *Journal of Entomological Research, 24*, 19–26.
6. Mishra, J., & Pandey, S. (2021). Advancements in lac processing and value addition techniques. *Indian Journal of Forest Research, 45*(2), 215–230.
7. Roonwal, M. L., Raizada, M. B., Chatterjee, R. N., & Singh, B. (1958). *Descriptive account of the host plants of the lac insect, Laccifer lacca (Kerr), and the allied plants in the Indian region (Parts 1 & 2)* (p. 140). Indian Lac Cess Committee.
8. Roy, A., & Sharma, K. K. (2010). Lac and livelihood: Role of lac cultivation in the tribal economy of India. *Journal of Rural Development, 29*(3), 307–315.

9. Sharma, K. K., Jaiswal, A. K., & Kumar, K. K. (2006). Role of lac culture in biodiversity conservation. *Current Science, 91*(8), 894–898.
10. Sharma, K. K., & Ramani, R. (2010). *Recent advances in lac culture* (pp. 1–391). IINRG.
11. Srinivasan, M. M. (1956). Lac, its cultivation and manufacture in India: Chapter IV—Host plants of the lac insect. *Indian Forester, 82*, 180–193.
12. Varshney, R. K., & Teotia, T. P. S. (1967). A supplementary list of the host plants of lac insects. *Journal of the Bombay Natural History Society, 64*, 488–511.
13. Yogi, R. K., Bhattacharya, A., Jaiswal, A. K., & Kumar, A. (2015). *Lac, plant resins and gum statistics 2014: At a glance* (Bulletin No. 07/2015, pp. 1–68). ICAR–Indian Institute of Natural Resins and Gums, Ranchi.
14. Zhang, Z. (1993). Four new species of lac insects of the genera *Metachardia* and *Kerria* from China (Homoptera: Tachardiidae). *Oriental Insects, 27*, 273–286.

BIOMONITORING AS A TOOL FOR ENVIRONMENTAL QUALITY ASSESSMENT AND ECOLOGICAL RISK EVALUATION

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Abstract

Bio-monitoring is a vital environmental assessment approach that utilizes living organisms and their biological responses to evaluate ecosystem health and detect the presence and effects of pollutants. Unlike conventional chemical monitoring, which provides only instantaneous measurements of contaminant concentrations, biomonitoring offers integrated information on the biological impacts of environmental stressors over time. This chapter presents an overview of bio-monitoring, including its fundamental concepts, major components, and practical applications in environmental monitoring and risk assessment. Particular emphasis is placed on bio-indicators and biomarkers, which serve as essential tools for detecting ecological changes and contaminant exposure at various levels of biological organization. The chapter discusses the two principal approaches of bio-monitoring: active bio-monitoring, involving the controlled exposure of selected organisms through caging or transplantation techniques, and passive bio-monitoring, which relies on naturally occurring resident species to assess long-term environmental conditions. Methodologies, advantages, limitations, and commonly used organisms such as mussels, fish, macro-invertebrates, diatoms, lichens, and mosses are reviewed. Several notable case studies, including the Mussel Watch Program in the United States, caged fish assessments in European rivers, freshwater mussel monitoring in the Ganga River, and biomonitoring studies in the Yamuna and Damodar river systems of India, demonstrate the effectiveness of biological monitoring in detecting heavy metals, organic pollutants, pesticides, and other contaminants. The findings highlight the importance of biomonitoring as a cost-effective, ecologically relevant, and scientifically robust tool for evaluating environmental quality, identifying pollution trends, and supporting environmental management strategies. Furthermore, the integration of biomarkers, bioaccumulation studies, community-level indices, and emerging technologies is enhancing the accuracy and predictive capability of biomonitoring programs. As concerns regarding environmental pollution, ecosystem degradation, and climate change continue to grow, bio-monitoring remains indispensable for ecological conservation, environmental policy development, and sustainable resource management.

Keywords: Biomonitoring, Bioindicators, Biomarkers, Active Biomonitoring, Passive Biomonitoring, Ecotoxicology, Environmental Monitoring, Bioaccumulation, Aquatic Ecosystems, Environmental Risk Assessment.

Introduction

Biomonitoring has emerged as a powerful and complementary approach to conventional environmental monitoring by utilizing living organisms and their biological responses to assess environmental conditions. The effectiveness of biomonitoring largely depends on the use of bioindicators and biomarkers. (Peakall, 1994; Walker *et al.,* 2012). Together, these tools provide early-warning signals of environmental degradation and help identify pollutant sources and ecological stress before irreversible damage occurs. Biomonitoring approaches are generally categorized into passive and active biomonitoring. A diverse range of organisms has been employed as biomonitors, including mussels, fish, macroinvertebrates, diatoms, lichens, mosses, and freshwater clams. These organisms differ in their sensitivity, ecological relevance, and pollutant accumulation capacities, making them suitable for specific monitoring objectives. Numerous biomonitoring programs worldwide have demonstrated the value of biological assessment in detecting pollution trends and evaluating environmental quality. This chapter provides a comprehensive overview of biomonitoring, including its principles, methodologies, major components, and practical applications. Particular emphasis is placed on bioindicators, biomarkers, active and passive biomonitoring approaches, and their role in environmental assessment and ecological risk evaluation. Furthermore, selected case studies are discussed to illustrate the effectiveness of biomonitoring in detecting environmental contamination and supporting evidence-based environmental management. As environmental challenges continue to intensify under the combined pressures of pollution, habitat degradation, and climate change, biomonitoring will remain a critical tool for safeguarding ecosystem health and promoting sustainable environmental stewardship.

Biomonitoring

Biomonitoring is the systematic use of living organisms or their responses to assess the quality and health of the environment, particularly with regard to the presence, concentration, and biological impact of pollutants or stressors. It involves quantitative or qualitative measurements of biological responses—ranging from molecular, cellular, physiological, to community-level changes—caused by environmental contaminants or ecological changes over time and space. (van der Oost *et al.,* 2003). It is a central component of ecotoxicology, conservation biology, and environmental risk assessment, used to detect early signs of environmental degradation, track contaminant pathways, and evaluate the effectiveness of pollution control measures. (van der Oost *et al.,* 2003; Resh and Rosenberg, 1993)

Types

- **Passive Biomonitoring:** Observing natural populations that have been exposed to environmental stressors over time
- **Active Biomonitoring:** Introducing selected organisms (e.g., via caging or transplanting) into an environment for controlled exposure.

Key Elements

Bioindicators

- Bioindicators are an important tool to monitor the health status of the aquatic ecosystem in order to detect the changes in the environment either positive or negative and their impacts upon human society (Plafkin *et al.,* 1989; Jain *et al.,* 2010; Khatri and Tyagi, 2015).
- Species or communities whose presence, abundance, or behavior reflects environmental conditions.

Biomarkers

- "A biomarker is any biological response to an environmental chemical at the individual level or below, indicating a deviation from normal biological status, due to exposure to contaminants."

  — Peakall (1994); Walker et al. (2012)
- A biomarker (short for *biological marker*) is a measurable biological response or indicator that reflects exposure to, or effects of, environmental pollutants in an organism.

Applications

- Monitoring heavy metal contamination using mussels (*Mytilus spp.*).
- Using macroinvertebrate community indices to assess freshwater quality.
- Measuring enzyme activity in fish to indicate exposure to organic pollutants. (Cairns & Pratt, 1993).

Active Biomonitoring

Active biomonitoring (ABM) refers to the deliberate exposure of selected organisms (usually transplanted or caged) to a particular environment to evaluate the presence and effects of pollutants over time. This approach is experimental and controlled, as opposed to passive biomonitoring, which relies on native species already present in the ecosystem.

Purpose and Advantages

- Standardization
- Temporal monitoring
- Detection of sublethal effects
- Comparative studies

Methodology

Selection of Organism

- Tolerant to handling and transport.
- Accumulates contaminants proportionally to environmental concentrations.
- Relevant to ecological food chains.

Deployment

- Organisms are caged or enclosed in permeable containers.
- Placed in targeted field sites (e.g., rivers, estuaries, lakes, industrial zones).
- Left for days to several weeks.

Analysis

- Bioaccumulation: Heavy metals, PCBs, PAHs, etc.
- Biomarkers: Enzyme activity, oxidative stress, genotoxicity, etc.
- Physiological responses: Growth rate, survival, reproduction

Commonly Used Organisms

Organism	**Type**	**Reason for Use**	**Pollutants Detected**	**References**
Mytilus spp.	Marine bivalves	Good metal accumulation, easy to cage	Heavy metals (Cd, Pb, Hg), PAHs, PCBs	NOAA (2007); Phillips & Rainbow (1993); Goldberg *et al.* (1978)
Oncorhynchus mykiss (Rainbow trout)	Freshwater fish	Widely studied biomarkers	Organic pollutants (PAHs), PCBs, EDCs, metals	Schwaiger *et al.* (2004); van der Oost *et al.* (2003)

Daphnia magna	Zooplankton	Short lifecycle, sensitive to toxins	Pesticides, pharmaceuticals, metals, nanoparticles	Barata *et al.* (2005); OECD (2004)
Limnodrilus hoffmeisteri	Oligochaete worm	Sediment exposure studies	Sediment-bound metals (Zn, Cu, Pb), PCBs, hydrocarbons	Chapman *et al.* (1992); Crane *et al.* (1995)
Corbicula fluminea	Freshwater clam	Used in river biomonitoring	Heavy metals (As, Cr, Hg), nutrients, EDCs	Graney *et al.* (1984); Farris *et al.* (1988)

Examples and Case Studies

1. Mussel ***Watch Program (USA)***

Organism: ***Mytilus edulis*** **and** ***Mytilus californianus***

Description: Long-term monitoring of metal and organic pollutants in coastal waters.

The Mussel Watch Program is the longest continuous contaminant monitoring program in U.S. coastal waters. Initiated by the National Oceanic and Atmospheric Administration (NOAA) in 1986, its primary goal is to monitor and assess spatial and temporal trends of chemical contaminants in U.S. estuarine and coastal environments using bivalve mollusks, mainly mussels (*Mytilus edulis*, *Mytilus californianus*) and oysters (*Crassostrea virginica*). O'Connor, T. P. (2002).

Key Findings & Contributions

- Reduction in legacy contaminants like DDT and PCBs over decades due to regulations (e.g., U.S. EPA bans).
- Persistent pollution in urban harbors (e.g., San Francisco Bay, New York Harbor).
- Data used in coastal management, restoration, and risk assessment.

2. Caged Fish in European Rivers

Organism: ***Oncorhynchus mykiss***

Parameters: EROD activity, bile metabolites for PAHs.

Findings: Effective in assessing industrial effluents and urban runoff.

Schwaiger, J., *et al.* (2004).

The use of caged fish, particularly rainbow trout, is a widely accepted active biomonitoring technique for assessing water quality in urbanized and industrialized water bodies. This method offers controlled exposure conditions and can help detect sublethal effects of pollutants that may not be evident from chemical analysis alone. This study by Schwaiger *et al.* (2004) was conducted in Germany to evaluate the biological impact of treated municipal wastewater effluents on aquatic environments.

Key Findings

- EROD activity was significantly higher in fish exposed downstream of wastewater treatment plants, indicating induction of detoxification enzymes by organic micropollutants.
- Bile metabolite concentrations were also elevated, suggesting substantial PAH exposure, even in treated wastewater.
- Histopathological observations showed mild liver damage and inflammatory responses, confirming biological effects even when chemical concentrations were below regulatory thresholds.
- The study demonstrated that treated effluents still contained biologically active contaminants capable of inducing sublethal stress in aquatic organisms.

Caging Freshwater Mussels in Contaminated Sites (India)

- Organism: *Lamellidens marginalis* (Indian freshwater mussel)
- Location: Ganga River at industrially impacted sites.
- Biomarkers: Lysosomal membrane stability, glutathione levels. [Kumar, R. N., *et al.* (2006)].

This case study focuses on the use of Indian freshwater mussels (*Lamellidens marginalis*) as bioindicators in active biomonitoring programs in industrial zones along the Ganga River. The primary aim was to evaluate the toxicological impact of industrial effluents on aquatic organisms by analyzing sublethal biochemical biomarkers in caged mussels.

Source: https://pml.ac.uk/wp-content/uploads/2024/08/attachment-733.jpeg

Key Findings

- Bioaccumulation of metals such as cadmium, lead, and zinc was notably higher in mussels caged at industrial sites compared to controls.
- The study confirmed sublethal toxicity despite no visible mortality, emphasizing the importance of biochemical biomarkers in early detection.

Limitations of Active Biomonitoring

- Stress from caging may influence results.
- Limited to organisms that tolerate handling and captivity.
- Requires repeated field visits and laboratory analysis.

Passive Biomonitoring:

- Passive biomonitoring refers to the observation and study of naturally occurring (resident) organisms in their unaltered native habitat to assess environmental quality.
- Unlike active biomonitoring, there is no artificial exposure or relocation of organisms. Instead, scientists evaluate biological responses in free-living populations that have been chronically exposed to environmental stressors (e.g., pollutants, habitat alteration, climate changes).
- It is a non-invasive, ecologically relevant method that reflects long-term and integrated effects of multiple stressors in complex environmental settings.

Advantages and Disadvantages*:*

- Long-term exposure assessment under natural conditions.
- Reflects cumulative and interactive effects of environmental stressors.
- No need for organism transplantation or artificial setups.
- Provides real-world data with ecological relevance.
- Limited control over confounding factors (e.g., predation, competition).

Methodology

- Site selection across pollution gradients.
- Sampling of resident organisms from air, water, soil, or sediment.
- Assessment of biological endpoints:
  - Species diversity and abundance.
  - Bioaccumulation of contaminants.
  - Biomarker analysis (e.g., enzyme activity, histopathology).

Examples

Organism	Environment	Pollutants Detected	Examples	References
Macroinvertebrates	Freshwater	Organic pollution, low DO, eutrophication, sediment stress	EPT taxa (Ephemeroptera, Plecoptera, Trichoptera) used in river bioassessment	Resh & Rosenberg (1993); Trivedi & Goel (1986)
Diatoms (microalgae)	Freshwater	pH, conductivity, salinity, nutrients	Community structure and indices (e.g., TDI – Trophic Diatom Index) used to monitor river health	Kelly (1998); Stoermer & Smol (1999)
Lichens	Terrestrial / Air	SO_2, NOx, heavy metals, ozone	Epiphytic lichens like *Parmelia* spp. used in urban-industrial air pollution monitoring	Conti & Cecchetti (2001); Nimis *et al.* (2002)
Mosses	Terrestrial / Air	Atmospheric deposition of heavy metals (Pb, Cd, Zn, Hg)	*Pleurozium schreberi*, *Hypnum cupressiforme* used in pan-European moss surveys	Harmens *et al.* (2008); *Fernández et al.* (2000)
Fish	Freshwater / Marine	Bioaccumulation of metals, PAHs, PCBs, endocrine disruptors	Native species (e.g., *Clarias batrachus*, *Oreochromis niloticus*) studied for tissue pollutants	van der Oost *et al.* (2003); Authman *et al.* (2015); Giguère *et al.* (2004)

Case Study

1. **Impact of Pesticides and Industrial Chemicals on Benthic Macroinvertebrates in the Yamuna River, India.**

Location: Yamuna River, particularly the stretch near Panipat and Delhi industrial zones, where both agricultural runoff (pesticides) and industrial discharges (chemicals and heavy metals) enter the river system.

Objective: To assess the response of benthic macroinvertebrates to contamination from pesticides (from agriculture) and industrial chemicals (from textile, paper, and electroplating industries).

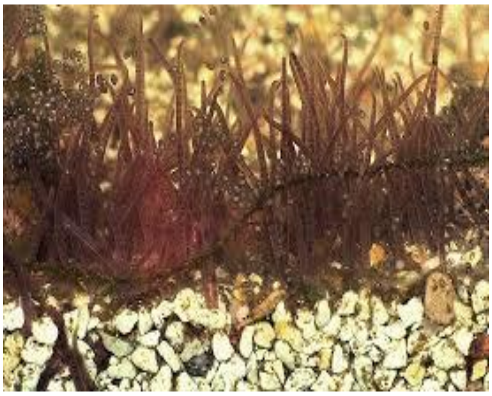
Key Benthic Findings

- DDT and endosulfan residues were found above permissible limits at downstream sites.
- Macroinvertebrate diversity dropped significantly from 12–15 taxa at the reference site to just 3–5 taxa near polluted discharge zones.
- Community structure shifted from Ephemeroptera–Trichoptera–Odonata (ETO) complex to Chironomid–Oligochaete dominance.

Site Type	Dominant Taxa	Interpretation
Heavily Polluted	*Chironomus spp., Tubifex tubifex*	Highly tolerant, thrive in toxic, low-oxygen sediment
Moderately Polluted	*Limnodrilus spp., Branchiura spp.*	Moderately tolerant, some opportunistic species
Reference Site	*Ephemeroptera, Trichoptera, Odonata*	Pollution-sensitive; absent in polluted zones

***Chironomus* species**

***Branchiura* spp**



Tubifex tubifex

Conclusion

This case study clearly shows that pesticides and industrial chemicals have a profound impact on the structure and diversity of benthic communities. The dominance of tolerant taxa such as *Chironomus* and *Tubifex* can serve as biological indicators of chemical stress, making benthic organisms ideal for long-term Arora, M., & Mehra, R. (2020).

2. **Bioaccumulation and health risk assessment of heavy metals in freshwater fishes collected from polluted stretches of the river Ganga and Yamuna, India.**
    - Species: *Clarias batrachus*, *Labeo rohita*

Findings

- High levels of Pb, Cr, Cd in fish from downstream Yamuna stretch.
- Liver and gills showed greater metal accumulation than muscle tissue.
- Risk assessment indicated that human consumption of these fish could exceed WHO tolerable intake levels (Kumar and Nagpure, 2021).

3. **Bioaccumulation of heavy metals in edible fish from industrial areas of Damodar River and associated health risks**
    - Species: *Clarias batrachus* and *Mystus tengara*
    - Contaminants: As, Hg, Cd, Pb
    - Outcome:
        - Fish tissues from industrial zones showed bioaccumulation levels exceeding FAO/WHO limits.
        - Muscle tissues showed accumulation of mercury (Hg) in concentrations dangerous for human consumption (Ghosh and Biswas, 2022).

Clarias batrachus

Mystus tengara

Applications

- River and lake ecosystem health assessments.
- Air quality assessments near urban/industrial zones.
- Baseline studies before and after restoration or remediation.

- Policy-making (e.g., Water Framework Directive, CPCB guidelines).

Conclusion

Biomonitoring serves as an essential and scientifically robust approach for assessing environmental quality and ecological health. Unlike traditional chemical monitoring, which provides only snapshot data, biomonitoring offers integrated, time-sensitive insights into the presence, persistence, and biological effects of pollutants on living organisms. It utilizes a wide range of bioindicators—such as fish, macroinvertebrates, algae, mosses, and lichens—to detect both acute and chronic exposures to contaminants. With growing concerns over emerging pollutants, ecotoxicological risks, and climate change, biomonitoring has become critical in environmental policy, risk assessment, and sustainable resource management. Techniques like passive and active biomonitoring, the use of biomarkers, and community-level indices (e.g., BMWP, EPT, ASPT) have enhanced the precision and relevance of ecological assessments. Moreover, biomonitoring supports early warning systems, enabling rapid response to ecosystem stressors before irreversible damage occurs. In conclusion, biomonitoring bridges ecology and toxicology, providing a powerful, cost-effective, and holistic framework for evaluating environmental integrity. As scientific methodologies advance, the integration of molecular tools, remote sensing, and machine learning with biomonitoring is expected to revolutionize environmental monitoring practices globally.

References

1. Arora, M., & Mehra, R. (2020). Impact of pesticides and industrial chemicals on benthic macroinvertebrate communities in the Yamuna River, India. *Environmental Monitoring and Assessment*, 192(8), 1–15.
2. Authman, M. M. N., Zaki, M. S., Khallaf, E. A., & Abbas, H. H. (2015). Use of fish as bio-indicator of the effects of heavy metals pollution. *Journal of Aquaculture Research & Development*, 6(4), 328–340.
3. Barata, C., Baird, D. J., & Soares, A. M. V. M. (2005). Demographic responses of a tropical cladoceran to pesticide stress. *Environmental Toxicology and Chemistry*, 24(2), 411–419.
4. Cairns, J., & Pratt, J. R. (1993). A history of biological monitoring using benthic macroinvertebrates. In D. M. Rosenberg & V. H. Resh (Eds.), *Freshwater Biomonitoring and Benthic Macroinvertebrates* (pp. 10–27). Chapman & Hall.
5. Chapman, P. M., Power, E. A., & Dexter, R. N. (1992). Sediment toxicity assessment and ecological risk evaluation. *Environmental Toxicology and Chemistry*, 11(6), 727–743.

6. Conti, M. E., & Cecchetti, G. (2001). Biological monitoring: Lichens as bioindicators of air pollution assessment—A review. *Environmental Pollution*, 114(3), 471–492.
7. Crane, M., Delaney, P., Watson, S., Parker, P., & Walker, C. H. (1995). The ecological relevance of biomarkers to environmental assessment. *Ecotoxicology*, 4(5), 315–326.
8. Farris, J. L., Cherry, D. S., & Cairns, J. Jr. (1988). The use of the Asiatic clam (*Corbicula fluminea*) in biomonitoring studies. *Environmental Toxicology and Chemistry*, 7(6), 523–528.
9. Fernández, J. A., Carballeira, A., & Aboal, J. R. (2000). Biomonitoring metal deposition in Galicia (NW Spain) with mosses. *Science of the Total Environment*, 254(1), 31–44.
10. Ghosh, A., & Biswas, N. K. (2022). Bioaccumulation of heavy metals in edible fish from industrial areas of the Damodar River and associated human health risks. *Environmental Science and Pollution Research*, 29(18), 26534–26547.
11. Giguère, A., Campbell, P. G. C., Hare, L., McDonald, D. G., & Rasmussen, J. B. (2004). Influence of lake chemistry and fish age on cadmium, copper, and zinc concentrations in fish. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(3), 387–398.
12. Goldberg, E. D., Bowen, V. T., Farrington, J. W., Harvey, G., Martin, J. H., Parker, P. L., Risebrough, R. W., Robertson, W., Schneider, E., & Gamble, E. (1978). The Mussel Watch. *Environmental Conservation*, 5(2), 101–125.
13. Graney, R. L., Cherry, D. S., Cairns, J. Jr., & Guttman, S. I. (1984). The Asiatic clam (*Corbicula fluminea*) as a biological monitor of water quality. *Environmental Toxicology and Chemistry*, 3(1), 47–56.
14. Harmens, H., Norris, D. A., Cooper, D. M., Mills, G., Steinnes, E., Kubin, E., Thöni, L., Aboal, J. R., Alber, R., Carballeira, A., *et al.* (2008). Mosses as biomonitors of atmospheric heavy metal deposition: Spatial patterns and temporal trends in Europe. *Environmental Pollution*, 158(10), 3144–3156.
15. Jain, C. K., Sharma, M. K., & Singh, S. (2010). Assessment of water quality using biological indicators. *Environmental Monitoring and Assessment*, 165(1–4), 591–603.
16. Kelly, M. G. (1998). Use of the trophic diatom index to monitor eutrophication in rivers. *Water Research*, 32(1), 236–242.
17. Khatri, N., & Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science*, 8(1), 23–39.
18. Kumar, A., & Nagpure, N. S. (2021). Bioaccumulation and health risk assessment of heavy metals in freshwater fishes collected from polluted stretches of the Ganga and Yamuna Rivers, India. *Environmental Monitoring and Assessment*, 193(4), 1–17.

19. Kumar, R. N., Solanki, R., & Kumar, J. I. N. (2006). Biomonitoring of industrial pollution in the Ganga River using freshwater mussels (*Lamellidens marginalis*). *Environmental Monitoring and Assessment*, 116(1–3), 89–101.
20. National Oceanic and Atmospheric Administration (NOAA). (2007). *Mussel Watch Program: National Status and Trends Program for Marine Environmental Quality*. NOAA Technical Memorandum NOS NCCOS.
21. Nimis, P. L., Scheidegger, C., & Wolseley, P. A. (2002). *Monitoring with Lichens — Monitoring Lichens*. Springer.
22. OECD. (2004). *OECD Guidelines for the Testing of Chemicals: Daphnia sp., Acute Immobilisation Test*. Organisation for Economic Co-operation and Development, Paris.
23. O'Connor, T. P. (2002). National distribution of chemical concentrations in mussels and oysters in the USA. *Marine Environmental Research*, 53(2), 117–143.
24. Peakall, D. B. (1994). The role of biomarkers in environmental assessment (1). Introduction. *Ecotoxicology*, 3(3), 157–160.
25. Phillips, D. J. H., & Rainbow, P. S. (1993). *Biomonitoring of Trace Aquatic Contaminants*. Springer.
26. Plafkin, J. L., Barbour, M. T., Porter, K. D., Gross, S. K., & Hughes, R. M. (1989). *Rapid Bioassessment Protocols for Use in Streams and Rivers*. U.S. Environmental Protection Agency, EPA/444/4-89-001.
27. Resh, V. H., & Rosenberg, D. M. (1993). *Freshwater Biomonitoring and Benthic Macroinvertebrates*. Chapman & Hall.
28. Schwaiger, J., Ferling, H., Mallow, U., Wintermayr, H., & Negele, R. D. (2004). Toxic effects of treated wastewater on rainbow trout (*Oncorhynchus mykiss*): Biomarker responses and histopathological changes. *Aquatic Toxicology*, 68(3), 257–272.
29. Stoermer, E. F., & Smol, J. P. (1999). *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge University Press.
30. Trivedi, R. K., & Goel, P. K. (1986). *Chemical and Biological Methods for Water Pollution Studies*. Environmental Publications.
31. van der Oost, R., Beyer, J., & Vermeulen, N. P. E. (2003). Fish bioaccumulation and biomarkers in environmental risk assessment: A review. *Environmental Toxicology and Pharmacology*, 13(2), 57–149.
32. Walker, C. H., Sibly, R. M., Hopkin, S. P., & Peakall, D. B. (2012). *Principles of Ecotoxicology* (4th ed.). CRC Press.

EMERGING TRENDS, TECHNOLOGICAL INNOVATIONS AND FUTURE DIRECTIONS IN ANIMAL SCIENCE

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Abstract

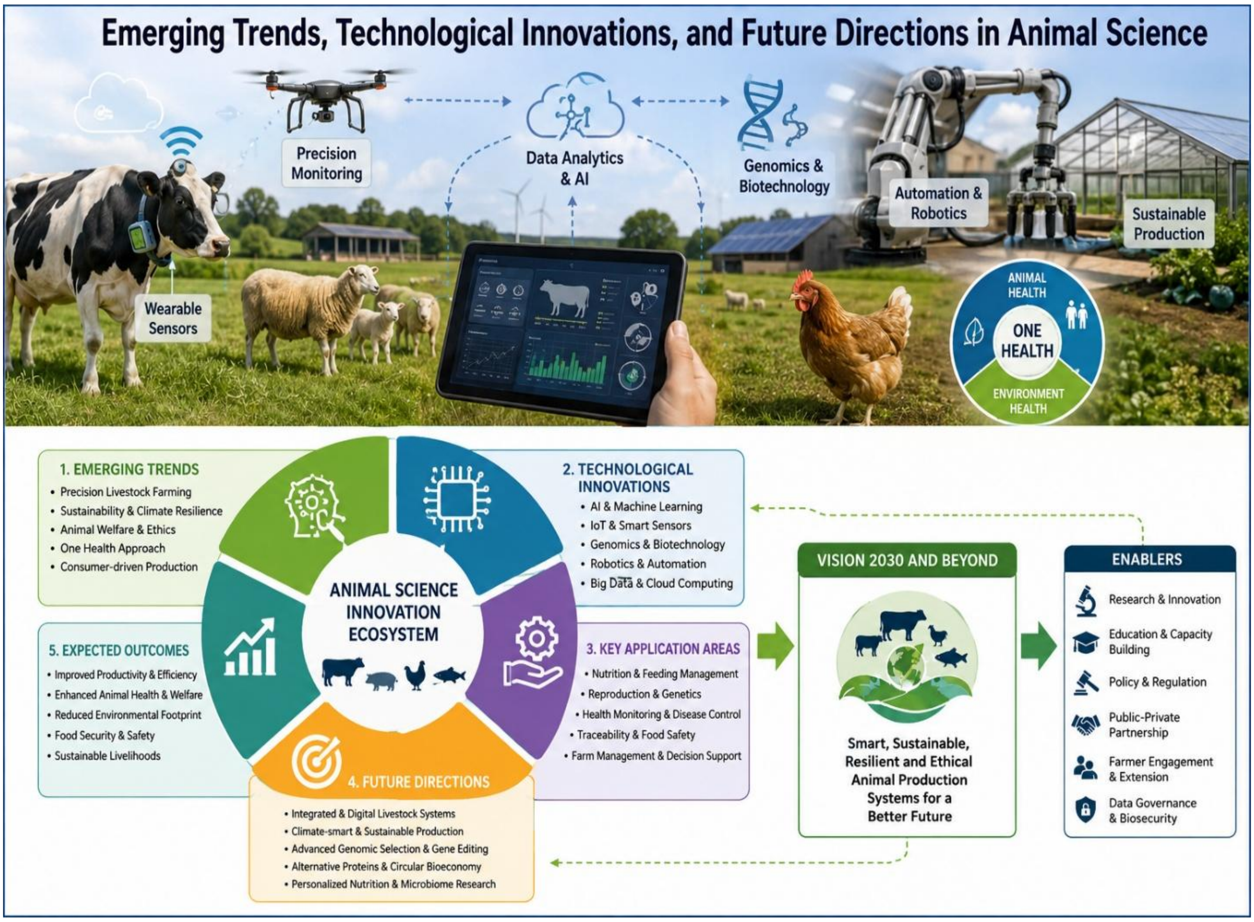
Technological developments, concerns about sustainability, and the increasing need for high-quality, safe goods derived from animals are driving a rapid shift in animal science. Conventional livestock production methods are changing due to emerging concepts including precision livestock farming, climate-smart animal agriculture, and the One Health approach. Artificial intelligence, the Internet of Things (IoT), genomics, gene editing, robots, and big data analytics are examples of technological advancements that are improving resource efficiency, production, animal health, and welfare. Sustainable and resilient production systems are being further enhanced by developments in animal nutrition, reproductive technologies, and disease control. However, the industry also has to deal with serious issues including climate change, antibiotic resistance, environmental sustainability, and the uptake of cutting-edge technologies, especially in poor nations. In order to increase output while reducing environmental effects, future approaches in animal science will prioritize the combination of biotechnology, digital technologies, and precision management techniques. In order to promote innovation and guarantee sustainable livestock development, cooperation between researchers, legislators, industry players, and farmers will be crucial. In order to achieve sustainable, effective, and resilient animal production systems, this chapter examines the key new trends, technological advancements, and prospects that are influencing the development of animal science.

Keywords: Artificial Intelligence, Genomics, Biotechnology, Animal Science, Precision Livestock Farming, Sustainability, Animal Welfare, Climate Resilience, Smart Farming, and One Health.

1. Introduction

By enhancing the productivity, health, welfare, and sustainability of livestock and poultry production systems, animal science plays a critical role in guaranteeing global food and nutritional security. Animal breeding and genetics, nutrition, physiology, reproduction, health management, welfare, and livestock production are just a few of the many areas covered by the discipline. Animal science is now essential to solving issues with food security, environmental sustainability, and economic development since the world's population is predicted to continue growing and the demand for foods generated from animals is anticipated to increase significantly [17].

Because of scientific and technological advancements, animal production systems have changed significantly in recent decades. Data-driven and technologically enabled methods that improve productivity, efficiency, and animal care are gradually replacing traditional management techniques. A promising approach to improving livestock management is Precision Livestock Farming (PLF), which combines sensors, automated monitoring systems, artificial intelligence (AI), machine learning, and Internet of Things (IoT) technology. For farmers and livestock managers, these technologies enable ongoing monitoring of animal behavior, health, and productivity, allowing for early illness identification and well-informed decision-making [10; 23].



The need for resilient and sustainable livestock systems has been further highlighted by the growing concerns about zoonotic infections, environmental degradation, antimicrobial resistance (AMR), and climate change. Adopting resource-efficient and climate-smart production methods is necessary because livestock production is a major contributor to agricultural greenhouse gas emissions. As a result, the ideas of circular bio economy, climatic resilience, and sustainability have become essential elements of contemporary animal science research and development [21]. Furthermore, in animal research, the One Health framework—which acknowledges the interdependence of environmental, human, and animal health—has grown in popularity. Antimicrobial resistance, food safety issues, zoonotic disease outbreaks, and ecosystem health are just a few of the complex issues that this multidisciplinary approach encourages cooperative efforts to address. Recent research emphasizes the significance of integrated approaches for sustainable livestock development and the crucial role that animal husbandry plays in influencing One Health outcomes [19; 3]

2. Emerging Trends in Animal Science

- **Precision Livestock Farming and Digital Transformation**

The use of Precision Livestock Farming (PLF) is one of the most significant developments in modern animal science. To track animal health, behavior, productivity, and environmental conditions in real time, PLF incorporates cutting-edge technologies like sensors, wearable technology, artificial intelligence (AI), machine learning, drones, and the Internet of Things (IoT). Early disease identification, better feeding and breeding choices, and more effective farm management are all made possible by these technologies. Continuous monitoring systems reduce production losses and improve animal wellbeing by giving farmers data-driven insights [10; 23].

- **Sustainable and Climate-Smart Livestock Production**

Enhancing feed efficiency, lowering methane emissions, conserving water resources, and encouraging circular agricultural methods are all major areas of study for modern animal science. Adaptation and mitigation techniques that improve cattle resilience while reducing environmental effects are highlighted by climate-smart approaches. In order to promote global food security and environmental preservation, sustainable intensification aims to boost productivity without increasing resource consumption [21; 8].

- **Advances in Genomics and Biotechnology**

Animal breeding and genetic enhancement initiatives have been transformed by the quick advancement of biotechnology and genomics. Animals with increased production, disease resistance, feed efficiency, and stress tolerance are being developed thanks to genomic selection, marker-assisted breeding, whole-genome sequencing, and gene-editing technologies like CRISPR- Cas systems. These developments speed up genetic advancement and offer ways to deal with issues related to developing diseases and climate change [7]. Precision breeding and customized livestock management are becoming more feasible because to the integration of genetics with digital technology.

- **One Health and Animal Welfare Approaches**

The idea of "One Health," which acknowledges the connection of animal, human, and environmental health, has become a fundamental underpinning in animal science. To protect public health and ecosystem sustainability, animal scientists are concentrating more on disease surveillance, biosecurity protocols, and judicious use of antibiotics [19]. The implementation of welfare-friendly production techniques and computerized welfare assessment technology has been prompted concurrently by growing public concern for animal welfare [13].

3. Technological Innovations in Animal Science

- **Artificial Intelligence and Precision Livestock Farming**

By enhancing production, animal health, welfare, and environmental sustainability, technological advancements are transforming animal science. AI-driven systems gather and evaluate real-time data on animal behavior, health status, feed intake, and environmental variables using machine learning algorithms, sensors, cameras, and automated monitoring devices. By enabling early disease identification, production performance prediction, and prompt management actions, these technologies improve efficiency and lower financial losses [10; 23].

- **Technologies for Gene Editing and Genomics**

Genomic selection accelerates genetic improvement for characteristics including growth performance, feed efficiency, disease resistance, fertility, and product quality by identifying superior animals at a young age using DNA-based information. Furthermore, compared to traditional breeding techniques, gene-editing technologies like CRISPR-Cas9 present previously unheard-of possibilities for precisely and effectively introducing desired genetic features. According to Hayes *et al.* (2021) [7] and Van Eenennaam (2023) [20], these improvements are assisting in the development of livestock populations that are more adaptable to emerging illnesses, climate stress, and shifting production conditions.

- **Omics and Reproductive Technologies**

Artificial insemination, embryo transfer, in vitro fertilization (IVF), and sex-sorted semen are examples of modern reproductive technologies that have greatly increased cattle populations' genetic advancement and reproductive efficiency. These technologies improve animal productivity and health by enabling focused disease management techniques, personalized nutrition, and precision breeding [16].

- **Automation and Robotics**
- Systems for producing animals are increasingly incorporating automation and robotics. Labor efficiency and operational precision are enhanced by robotic milking systems, automated feeding equipment, manure management technologies, and autonomous farm vehicles. By offering prompt care and monitoring, these technologies increase animal welfare, decrease human involvement, and promote uniformity in management procedures [2].

4. Advancements in Animal Feeding and Nutrition

- **Intelligent Feeding Systems and Precision Nutrition**

The need to increase feed efficiency, boost animal performance, lower production costs, and lessen environmental effects has led to tremendous breakthroughs in animal nutrition in recent years. To maximize nutrient consumption while lowering feed waste and nutrient excretion, precision feeding systems make use of sensors, automated feeders, artificial intelligence (AI), and data analytics [15].

- **Alternative Feed Resources and Sustainable Ingredients**

The investigation of alternative feed ingredients has been prompted by worries about environmental sustainability and the growing competition for traditional feed resources. As sustainable substitutes for conventional protein sources, novel feed resources such insect meal, algae, seaweed, single-cell proteins, and agro-industrial byproducts are drawing interest. Feeds made from insects, especially those made from larvae of black army flies, have shown excellent nutritional value and minimal environmental impact. In a similar vein, seaweed and microalgae provide important amounts of vitamins, proteins, vital fatty acids, and bioactive substances that might enhance animal health and performance [11].

- **Functional Feed Additives and Gut Health Management**

The use of functional feed additives to improve gut health, immunity, and productivity is becoming more and more important in recent advancements in animal nutrition. Antibiotic growth promoters are frequently substituted by probiotics, prebiotics, symbiotics, phytogenic substances, organic acids, and enzymes. These chemicals augment immune responses, increase nutritional digestibility, support a healthy gut micro biome, and improve animal performance [1].

5. New Methods for Animal Welfare and Health

- **Accurate Management of Animal Health**

To continually monitor the health and behavior of animals, Precision Animal Health Management (PAHM) combines sensors, wearable technology, biosensors, artificial intelligence (AI), and machine learning algorithms. Before clinical symptoms appear, these technologies help identify illnesses, metabolic abnormalities, and stress-related conditions. In order to reduce the incidence of disease and increase productivity, real-time monitoring of physiological markers such body temperature, heart rate, rumination, and activity levels allows for prompt interventions [10; 14].

- **Advanced Technologies for Disease Surveillance and Diagnosis**

Infectious disorders can be quickly and accurately identified because to molecular diagnostic methods including polymerase chain reaction (PCR), next-generation sequencing (NGS), and biosensor-based detection systems. On-farm illness detection is made possible by portable diagnostic tools and point-of-care testing technologies, which shorten reaction times and minimize financial losses. Furthermore, predictive disease modeling is made easier by the integration of big data analytics and AI, which supports more successful biosecurity and health management techniques [6].

- **Innovations in Vaccines and Immunological Interventions**

For the management of animal diseases, recombinant vaccines, vector-based vaccines, DNA vaccines, and mRNA vaccine technologies are being investigated more and more. Compared to traditional immunizations, these cutting-edge vaccines provide better efficacy, safety, and flexibility. Interest in using mRNA technology for animal health has increased due to its success in human medicine, especially in the fight against trans boundary and developing animal diseases [12].

- **Animal Welfare Monitoring and Assessment Technologies**

Automated monitoring technologies have made it possible to objectively and continuously analyze animal wellbeing thanks to advancements in precision livestock production. Indicators including movement, eating habits, social interactions, and stress reactions are increasingly being assessed using cameras, computer vision systems, audio sensors, and behavioral analysis techniques. These technologies minimize human observation bias while offering trustworthy wellbeing estimates [13].

- **Combating Antimicrobial Resistance through Alternative Strategies**

Alternative strategies for illness prevention and treatment have been prompted by the growing global concern over antimicrobial resistance (AMR). As alternatives to traditional antibiotics, probiotics, prebiotics, phytogenic substances, bacteriophages, antimicrobial peptides, and immunomodulators are being studied more and more. These substitutes lower the likelihood of antibiotic resistance development, enhance gut micro biome balance, and preserve animal health [19].

6. Climate Resilience and Environmental Sustainability

- **Environmental Challenges in Livestock Production**

The industry contributes to emissions of greenhouse gases (GHGs), such as carbon dioxide (CO_2), nitrous oxide (N2O), and methane (CH_4), which are important causes of climate change. Water use, nutrient pollution, biodiversity loss, and land-use change are all impacted by livestock systems. In animal science, striking a balance between productivity and environmental sustainability has become crucial as the demand for foods generated from animals continues to grow [8].

- **Climate-Smart Livestock Production Systems**

In addition to improving resilience to climate-related challenges and lessening environmental effects, these systems seek to boost productivity. Better breeding programs, effective feeding methods, sustainable grazing management, and enhanced manure handling techniques are examples of climate-smart tactics. In order to adapt to rising temperatures and shifting climatic circumstances, it is especially crucial to produce cattle breeds that are resistant to heat and disease [17].

- **Nutritional and Management Strategies for Emission Reduction**

Seaweed, tannins, essential oils, and methane inhibitors are examples of feed additives that have shown great promise in lowering bovine enteric methane output. In addition to increasing animal productivity, balanced diets and better feed efficiency significantly lessen the environmental impact of each animal product produced [9].

Sustainable environmental practices are also aided by efficient manure management techniques. Anaerobic digestion is one technology that reduces methane emissions while producing sustainable energy by turning livestock manure into biogas. By using waste products as valuable agricultural resources, integrated crop-livestock systems further encourage nutrient recycling and support the principles of the circular bio economy [5].

- **Increasing Climate Resilience with Sustainable Development and One Health**

The One Health paradigm has become a key strategy for tackling the interrelated issues of environmental sustainability, human health, animal health, and climate change. The spread of diseases, the likelihood of zoonotic disease onset, and animal productivity can all be impacted by climate change. Building resilient livestock systems thus requires integrated management techniques that take public health, animal welfare, and ecosystem health into account [21].

7. Obstacles and Limitations in the Adoption of Technology

- **Economic and Financial Barriers**

Even though animal science technologies are developing quickly, a number of financial and economic obstacles prevent their widespread implementation. Precision livestock farming (PLF), robots, automated feeding systems, artificial intelligence (AI), and genomic tools are examples of modern technologies that frequently demand large upfront costs. For smallholder and resource-constrained farmers in particular, the expenses of buying equipment, setting up infrastructure, maintaining software, and providing technical support can be unaffordable. Technology adoption is further hampered in many developing nations by restricted access to financial incentives and credit facilities [4].

- **Infrastructure and Technical Limitations**

The implementation of smart livestock systems is hampered in many rural areas by poor internet connectivity, erratic electrical supplies, and restricted access to digital services. Large amounts of data are produced by precision agricultural technology, which necessitate reliable communication networks and cloud-based storage systems for efficient use. Furthermore, the efficacy of technology-driven management techniques may be diminished by farmers' and agricultural workers' lack of technical skills [22].

- **Data Management, Privacy, and Cyber security Concerns**

New data governance difficulties have been brought about by the growing reliance on digital technologies. Precision livestock systems gather a lot of data about farm operations, environmental conditions, animal health, and productivity. Producers and technology providers continue to have serious concerns about data ownership, privacy, sharing rights, and security. Farm operations may be jeopardized and trust in digital technology diminished by cyber security risks, such as unlawful access, data breaches, and system outages [18].

- **Ethical and Regulatory Challenges**

Significant ethical and legal issues are brought up by technological advancements like gene editing, artificial intelligence, and computerized animal management systems. Consumer acceptability and policy development may be impacted by public concerns about food safety, genetic alteration, animal welfare, and the moral application of biotechnology. Researchers, manufacturers, and industry stakeholders face uncertainty due to the fact that regulatory frameworks governing novel technologies frequently differ between nations. Particularly, public opinion, international trade regulations, and regulatory approval are obstacles to the commercialization of gene-edited animals [20].

- **Social Acceptance and Capacity Building**

Farmers may be deterred from implementing innovative methods by resistance to change, a lack of knowledge about the advantages of technology, and worries about losing their jobs. Additionally, older farmers and those with lower levels of digital literacy frequently have more trouble making efficient use of cutting-edge technologies. Therefore, developing the skills needed to manage technology-intensive livestock systems requires strengthening education, training programs, and extension services [4].

8. Future Directions in Animal Science

- **Artificial Intelligence and Digital Technology Integration**

The incorporation of artificial intelligence (AI), machine learning, big data analytics, and the Internet of Things (IoT) into livestock production systems will have a significant impact on animal research in the future. It is anticipated that precision livestock farming technology will go from monitoring instruments to all-encompassing decision-support systems that can forecast disease outbreaks, optimize feeding plans, increase reproductive efficiency, and improve animal wellbeing. Farmers will be able to make prompt, evidence-based management decisions thanks to the real-time data analysis made possible by the integration of AI with sensor networks and cloud-based platforms [10; 23].

- **Advances in Genomics and Precision Breeding**

In order to produce cattle with increased productivity, disease resistance, feed efficiency, and climate resilience, future breeding strategies are anticipated to integrate genomic selection, whole-genome sequencing, and gene-editing technologies like CRISPR-Cas systems. By preserving genetic variation and cutting down on breeding cycles, precision breeding techniques will make it possible to select animals with desired characteristics [7; 20].

- **Precision Nutrition and Advanced Animal Health Management**

In order to maximize nutrient absorption and enhance animal performance, future advancements in animal nutrition will depend more and more on precision feeding systems, nutrigenomics, microbiome research, and metabolomics. Individualized feeding plans for each animal will increase feed efficiency while reducing environmental effects. Concurrently, developments in wearable technology, molecular diagnostics, and biosensors will improve precision animal health management by facilitating early disease identification and focused therapies [14].

9. Policy Implications and Strategic Recommendations

- **Strengthening Research, Innovation, and Technology Transfer**

Supportive legislative frameworks that encourage research, innovation, and efficient technology transfer are essential given the speed at which animal science innovations are developing.

Investments in precision livestock farming, biotechnology, artificial intelligence (AI), genomics, and climate-smart livestock systems should be given top priority by governments and academic institutions. Increasing financing for multidisciplinary research can hasten the creation of creative answers to problems with disease control, sustainability, productivity, and animal welfare. Additionally, enhancing cooperation between academic institutions, research groups, business players, and livestock farmers might help translate scientific findings into useful applications [8].

- **Promoting Sustainable and Climate-Resilient Livestock Systems**

Animal agriculture faces substantial problems due to climate change, necessitating policy actions that support resilience and sustainability. Through financial incentives, carbon credit programs, and support initiatives for sustainable production systems, governments should promote the adoption of climate-smart livestock practices. The environmental impact of animal agriculture can be greatly decreased by policies that support integrated crop–livestock systems, methane mitigation technologies, efficient feed usage, and renewable energy production [21].

- **Strengthening Animal Health, Welfare, and One Health Frameworks**

In order to handle new global issues including zoonotic infections and antimicrobial resistance (AMR), effective policies are required to promote animal health and wellbeing. Livestock health and productivity can be enhanced by bolstering veterinarian services, disease surveillance systems, biosecurity protocols, and immunization campaigns. To address interrelated health concerns, national and international policy frameworks should adopt the One Health approach, which integrates human, animal, and environmental health [19].

- **Regulatory and Data Governance Frameworks**

Clear regulatory and data governance frameworks are necessary due to the growing use of biotechnology and digital technologies in animal science. Standards for data ownership, privacy, cyber security, and the moral application of AI and gene-editing technologies must be established by policymakers. While guaranteeing responsible innovation, harmonized rules can enhance global trade, encourage consumer trust, and ease the adoption of new technologies [20].

Conclusion

Conventional livestock production systems are being reshaped by emerging trends like precision livestock farming, climate-smart agriculture, genomics, artificial intelligence, and the One Health approach. These developments present opportunities to enhance animal health, welfare, productivity, and environmental sustainability. More effective, data-driven, and sustainable management techniques are being made possible by advancements in animal nutrition, biotechnology, reproductive technologies, and digital monitoring systems. At the same time, production processes and policy choices are being impacted by growing consumer awareness of environmental stewardship, animal welfare, and food safety. Despite these developments, there are still a number of obstacles that could prevent such technologies from being widely adopted, such as high implementation costs, poor infrastructure, a lack of technical know-how, data governance issues, and complicated regulations. The effective integration of biotechnology, digital technologies, sustainable production methods, and interdisciplinary cooperation will be critical to the future of animal research. To provide fair access to technical developments and optimize their advantages across various production systems, strategic investments in research, innovation, education, and supportive policy frameworks will be crucial. In the end, the convergence of innovation, sustainability, and scientific advancement provides a route toward livestock systems that are more robust, effective, and ecologically conscious, supporting both sustainable agricultural development and global food security.

References

1. Adhikari, P., & Kim, W. K. (2023). Overview of alternatives to antibiotics in poultry production: Probiotics, prebiotics, and phytogenic feed additives. *Animals, 13*(4), 678. https://doi.org/10.3390/ani13040678
2. Banhazi, T. M., Black, J. L., & Rutley, D. L. (2023). Emerging automation technologies for livestock production systems. *Animal Production Science, 63*(12), 1055–1068. https://doi.org/10.1071/AN22345
3. Botes, M., Mears, C., Koen, J., & colleagues. (2024). The application of the One Health approach in the management of five major zoonotic diseases using the World Bank domains: A scoping review. *One Health, 18*, 100695. https://doi.org/10.1016/j.onehlt.2024.100695
4. Eastwood, C., Renwick, A., Nettle, R., Dela Rue, B., & Gray, D. (2023). Challenges and opportunities for the adoption of precision livestock farming technologies. *Animal Production Science, 63*(10), 897–910. https://doi.org/10.1071/AN22156
5. Food and Agriculture Organization. (2023). *The state of food and agriculture 2023: Revealing the true cost of food to transform agrifood systems*. FAO. https://doi.org/10.4060/cc7724en
6. Gautam, R., Ghatak, S., Kumar, A., & Singh, B. (2023). Emerging diagnostic technologies for animal disease surveillance and control. *Veterinary Research Communications, 47*(4), 1465–1482. https://doi.org/10.1007/s11259-023-10123-4
7. Hayes, B. J., Daetwyler, H. D., Bowman, P. J., Moser, G., Tier, B., Crump, R. E., Khatkar, M. S., Raadsma, H. W., & Goddard, M. E. (2021). Genomic prediction from whole

genome sequence in livestock: The 1000 Bull Genomes Project. *Animal Production Science, 61*(19), 2065–2074. https://doi.org/10.1071/AN20395

8. Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Bodirsky, B. L., Pradhan, P., Barrett, C. B., Benton, T. G., Hall, A., Pikaar, I., Bogard, J. R., Bonnett, G. D., Bryan, B. A., Campbell, B. M., Christensen, S., Clark, M., Fanzo, J., Godde, C. M., Jarvis, A., ... Rockström, J. (2021). Innovation can accelerate the transition toward a sustainable food system. *Nature Food, 2*(5), 266–272. https://doi.org/10.1038/s43016-021-00261-7
9. Hristov, A. N., Kebreab, E., Niu, M., Oh, J., Bannink, A., Bayat, A. R., Boland, T. M., Brito, A. F., Casper, D. P., Crompton, L. A., Dijkstra, J., Eugène, M., Garnsworthy, P. C., Huhtanen, P., Kreuzer, M., Lund, P., Martin, C., McGee, M., Moate, P. J., ... Yu, Z. (2022). Symposium review: Uncertainties in enteric methane inventories, measurement techniques, and prediction models. *Journal of Dairy Science, 105*(11), 8782–8801. https://doi.org/10.3168/jds.2021-21493
10. Kirkwood, R. N., Alhamad, M. N., et al. (2024). Scoping review of precision technologies for cattle monitoring. *Smart Agricultural Technology, 9*, 100596. https://doi.org/10.1016/j.atech.2024.100596
11. Makkar, H. P. S., Tran, G., Heuzé, V., & Ankers, P. (2023). State-of-the-art on use of insects as animal feed. *Animal Feed Science and Technology, 302*, 115706. https://doi.org/10.1016/j.anifeedsci.2023.115706
12. Meeusen, E. N. T., Walker, J., Peters, A., Pastoret, P. P., & Jungersen, G. (2024). Current status and future prospects of vaccines for veterinary applications. *Veterinary Immunology and Immunopathology, 269*, 110830. https://doi.org/10.1016/j.vetimm.2024.110830
13. Mota-Rojas, D., Napolitano, F., Strappini, A., Orihuela, A., Ghezzi, M., Hernández-Ávalos, I., Mora-Medina, P., & Whittaker, A. L. (2023). Animal welfare and sustainability in livestock production systems: A global perspective. *Animals, 13*(8), 1346. https://doi.org/10.3390/ani13081346
14. Neethirajan, S. (2023). The role of artificial intelligence in animal health monitoring and precision livestock farming. *Computers and Electronics in Agriculture, 209*, 107848. https://doi.org/10.1016/j.compag.2023.107848
15. Pomar, C., & Remus, A. (2019). Precision pig feeding: A breakthrough toward sustainability. *Animal Frontiers, 9*(2), 52–59. https://doi.org/10.1093/af/vfz006
16. Rexroad, C., Vallet, J., Matukumalli, L. K., Reecy, J., Bickhart, D., Blackburn, H., Boggess, M., Cheng, H., Clutter, A., Cockett, N., Ernst, C., Fulton, J., Liu, G., Lunney, J., Maltecca, C., McKay, S., Plastow, G., Sonstegard, T., Taylor, J., & Tuggle, C. (2019).

Genome to phenome: Improving animal health, production, and well-being. *Animal Frontiers, 9*(4), 6–13. https://doi.org/10.1093/af/vfz029

17. Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management, 16*, 145–163. https://doi.org/10.1016/j.crm.2017.02.001
18. Rose, D. C., Wheeler, R., Winter, M., Lobley, M., & Chivers, C. A. (2021). Agriculture 4.0: Making it work for people, production, and the planet. *Land Use Policy, 100*, 104933. https://doi.org/10.1016/j.landusepol.2020.104933
19. Schmitt, H., Muloi, D., & colleagues. (2024). The impacts of animal agriculture on One Health—Bacterial zoonosis, antimicrobial resistance, and beyond. *One Health, 18*, 100748. https://doi.org/10.1016/j.onehlt.2024.100748
20. Van Eenennaam, A. L. (2023). Genetic technologies and gene editing in animal agriculture: Opportunities and challenges. *Annual Review of Animal Biosciences, 11*, 1–23. https://doi.org/10.1146/annurev-animal-021419-083803
21. Verkuijl, C., Smit, J., Green, J. M. H., Nordquist, R. E., Sebo, J., Hayek, M. N., & Hötzel, M. J. (2024). Climate change, public health, and animal welfare: Towards a One Health approach to reducing animal agriculture's climate footprint. *Frontiers in Animal Science, 5*, 1281450. https://doi.org/10.3389/fanim.2024.1281450
22. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2023). Big data and smart farming technologies in livestock production: Opportunities and challenges. *Agricultural Systems, 205*, 103566. https://doi.org/10.1016/j.agsy.2022.103566
23. Zhang, Y., Wang, H., Su, M., & Wang, X. (2023). Precision livestock farming research: A global scientometric review. *Animals, 13*(13), 2096. https://doi.org/10.3390/ani13132096

STUDIES ON BIOCHEMICAL CHANGES IN THE TISSUES OF *OPHIOCEPHALUS STRIATUS* AND *LABEO ROHITA* EXPOSED TO CYPERMETHRIN

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Abstract

The effect of cypermethrin on glycogen in liver and brain of *Ophiocephalus striatus and Labeo rohita* exhibited notable alterations. Liver and brain being the main site of metabolic activity in body was selected for the study purpose. The sublethal concentration of cypermethrin treated with *Ophiocephalus striatus* and *Labeo rohita* at different time interval and in the treated liver and brain, glycogen content showed decreased and increased trend respectively.

Keywords: Cypermethrin, *Ophiocephalus striatus*, *Labeo rohita,* Liver, Brain and Glycogen.

Introduction

Synthetic pyrethroid insecticides, particularly cypermethrin, are extensively used worldwide for controlling agricultural insect pests to enhance crop productivity. They are also widely applied in public health programs to control disease vectors such as mosquitoes, cockroaches, ticks, and flies. Although pyrethroids are considered relatively safe for mammals, they are several orders of magnitude more toxic to fish than many organophosphate insecticides they have replaced (Oros *et al.,* 2005). Their widespread use has therefore raised concerns regarding their impact on aquatic ecosystems.

Numerous studies have demonstrated that exposure to insecticides induces significant biochemical alterations in fish, affecting normal physiological and metabolic processes (Jebakumar *et al.,* 1990; Sultatos, 1998; Kamble and Muley, 2000; Prasad *et al.,* 2002). Among various organs, the liver is particularly susceptible to pesticide toxicity because of its central role in detoxification and metabolism. The greater vulnerability of the liver has been attributed to its relatively slow blood flow compared with cardiac output (Gingerich, 1982) and the close association of hepatocytes with the biliary system (Hinton and Lauren, 1990). Consequently, exposure to pesticides produces pronounced biochemical and physiological changes in hepatic tissues (Murty and Devi, 1982; Anthony *et al.,* 1986; Bhushan *et al.,* 2002).

Pesticides entering aquatic ecosystems persist in water bodies and become concentrated through bioaccumulation, bioconcentration, and biomagnification, ultimately posing serious risks to aquatic organisms (Murty, 1986). Toxic contaminants disrupt normal metabolic pathways and induce biochemical alterations in various tissues and organs of exposed animals (Sastry and Sharma, 1979). In fish, energy required for maintenance, growth, and stress adaptation is derived from the catabolism of carbohydrates, lipids, and proteins. Glycogen, the principal carbohydrate reserve, plays a vital role in maintaining glucose homeostasis and meeting increased energy demands during environmental stress. Exposure to toxic chemicals alters carbohydrate metabolism, leading to changes in glycogen reserves and other biochemical constituents. These molecular and biochemical responses often precede cellular and physiological dysfunction, making them valuable biomarkers for assessing environmental pollution and toxic stress.

The present study was therefore undertaken to investigate the alterations in glycogen content in the liver and brain tissues of the freshwater fishes *Ophiocephalus striatus* and *Labeo rohita* following exposure to sublethal concentrations of cypermethrin at different time intervals. The findings provide insights into the metabolic responses of fish to pesticide-induced stress and contribute to understanding the toxicological effects of cypermethrin on aquatic organisms.

Materials and Methods

Healthy specimens of the freshwater fishes *Ophiocephalus striatus* and *Labeo rohita*, measuring 12–30 cm in length and weighing 13–25 g, were collected from Wadali Lake, Amravati region, for the present investigation. The fishes were thoroughly washed and acclimatized under laboratory conditions before the commencement of the experiment. Following acclimatization, groups of six fishes were transferred to separate aquaria containing a sublethal concentration (0.0007 µ/L) of cypermethrin and exposed for different durations of 24, 48, 72, and 96 h. A corresponding control group was maintained under identical conditions without cypermethrin exposure. At the end of each exposure period, the fishes were sacrificed, and fresh liver and brain tissues were carefully dissected for biochemical analysis. Glycogen content in the tissues was estimated according to the method described by Kemp *et al.* (1954). The glycogen concentration was determined and expressed as mg/L. The obtained data were used to evaluate cypermethrin-induced alterations in carbohydrate metabolism of both fish species.

Results and Discussions

The impact of sublethal concentration of cypermethrin on glycogen level of in the liver and brain tissues of *Ophiocephalus striatus* and *Labeo rohita* observed at different time intervals.

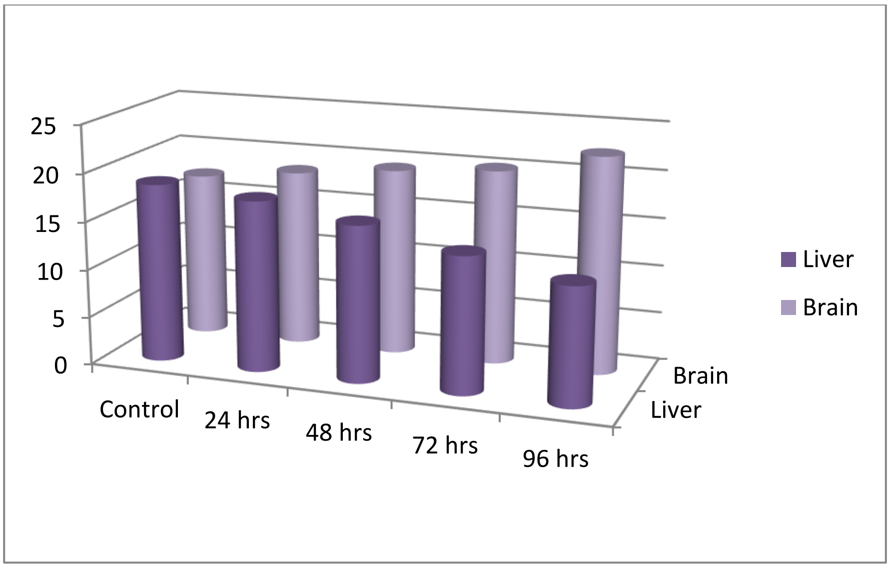

Figure 1: Effect of cypermethrin on glycogen (mg/g) of the fish *Ophiocephalus striatus* at different time intervals

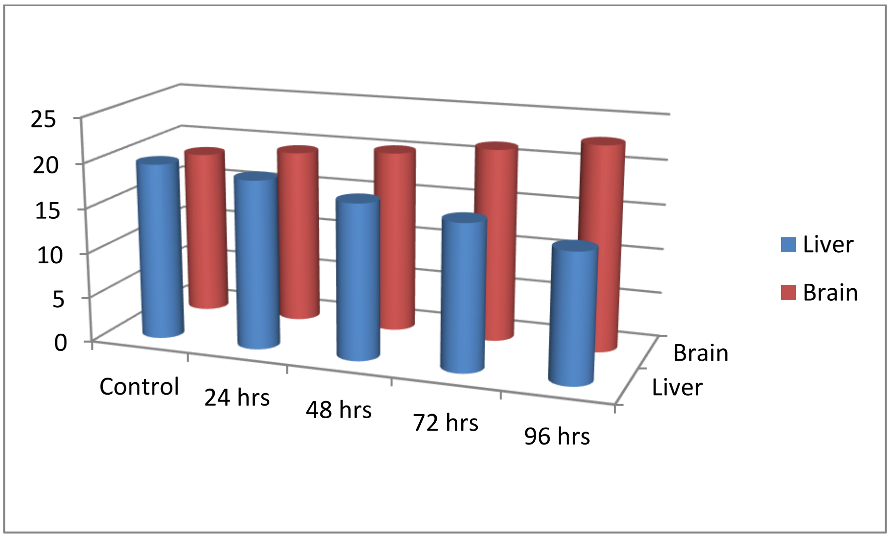

Figure 2: Effect of cypermethrin on glycogen (mg/g) of the fish *Labeo rohita* at different time intervals

The present investigation revealed a progressive decline in glycogen content in most tissues of the experimental fish with increasing duration of exposure up to 96 h, indicating depletion of energy reserves under toxic stress. Glycogen is the primary storage form of carbohydrates and serves as an immediate source of energy during adverse environmental conditions. The observed reduction in glycogen levels suggests enhanced glycogenolysis to meet the increased energy demand required for detoxification, maintenance of homeostasis, and survival under pesticide-induced stress. Such depletion reflects disturbances in carbohydrate metabolism and impaired physiological functioning of vital organs.

In contrast, the brain exhibited an increase in glycogen content compared with the control. This elevation may represent a compensatory adaptive response to maintain an adequate energy supply for neural tissues during toxic stress. The increased glycogen level could result from restoration of the regulatory balance between glycogen synthesis by glycogen synthetase and glycogen breakdown by phosphorylase, leading to enhanced glycogenesis from carbohydrate precursors or gluconeogenesis from non-carbohydrate substrates.

The biochemical alterations observed in the present study indicate functional impairment of tissues following toxicant exposure. Similar reductions in tissue glycogen content have been reported by *Susan et al.* (2010), who attributed glycogen depletion to enhanced metabolic activity under toxic stress. Likewise, *Somaiah et al.* (2015) reported a significant decrease in glycogen content in *Labeo rohita* exposed to organophosphate pesticides, suggesting increased utilization of carbohydrate reserves to meet elevated energy requirements. Furthermore, the significant increase in brain glucose levels observed during sublethal cypermethrin exposure is consistent with the findings of *Sarma et al.* (2010), who reported hyperglycemia in pesticide-exposed fish as a physiological stress response. Comparable observations were also documented by *Tripathy et al.* (2004), further supporting that pesticide exposure disrupts carbohydrate metabolism by altering glycogen utilization and glucose homeostasis in freshwater fishes.

References

1. Anthony, J., Banister, E., & Oloffs, P. C. (1986). Effect of sublethal level of diazinon: Histopathology of liver. *Bulletin of Environmental Contamination and Toxicology, 37*, 501–507.
2. Bhushan, P. B., Singh, M. K., & Rani, M. (2002). Dimethoate and monocil toxicity on the concentration of protein and amino acid in the serum and liver of *Channa marulius* (Ham.). *Nature Environment and Pollution Technology, 1*, 147–150.
3. Gingerich, W. H. (1982). Hepatic toxicology of fishes. In L. F. Weber (Ed.), *Aquatic toxicology* (pp. 55–105). Plenum Press.
4. Hinton, D. E., & Lauren, D. J. (1990). Integrative histopathological approaches to the detection of environmental stressors on fishes. *American Fisheries Society Symposium, 8*, 51–65.
5. Jebakumar, S. R., Floras, D., Ganesan, S. D. J., Jaga, R. M., Thisan, G., & Jaykumar, J. (1990). Effect of short-term sublethal exposure of cypermethrin on the organic constituents of the freshwater fish *Lepidocephalichthys thermalis*. *Journal of Environmental Biology, 11*, 203–209.

6. Kemp, A. A., Kits, J. M., & Van H. (1954). A colorimetric micromethod for the determination of glycogen in tissues. *Biochemical Journal, 56*, 646–648.
7. Kumble, G. B., & Muley, D. V. (2000). Effect of acute exposure of endosulfan and chlorpyrifos on the biochemical composition of the freshwater fish *Sarotherodon mossambicus*. *Indian Journal of Environmental Science, 4*, 97–102.
8. Murty, A. S., & Devi, P. A. (1982). The effect of endosulfan and its isomers on tissue protein, glycogen and lipid in the fish *Channa punctatus*. *Pesticide Biochemistry and Physiology, 17*, 280.
9. Murty, A. S. (1986). *Toxicity of pesticides to fish* (Vol. II). CRC Press.
10. Oros, D. R., Hoover, D., Rodigari, F., Crane, D., & Sericano, J. (2005). Levels and distribution of polybrominated diphenyl ethers in water, surface sediments and bivalves from the San Francisco Estuary. *Environmental Science & Technology, 39*, 33–41.
11. Prasad, B. B., Singh, K. M., & R. M. (2002). Dimethoate and monocil toxicity on the concentration of *Channa maruleus* (Ham.). *Nature Environment and Pollution Technology, 1*, 147–150.
12. Sarma, K., Pal, A. K., Sahu, N. P., Mukherjee, S. C., & Baruah, K. (2010). Biochemical and histological changes in the brain tissue of spotted murrel, *Channa punctatus* (Bloch), exposed to endosulfan. *Fish Physiology and Biochemistry*.
13. Sastry, K. V., & Sharma, S. K. (1979). Toxic effect of endrin on liver and kidney of teleost fish. In *Proceedings of the Symposium on Environmental Biology*, Muzaffarnagar, India (pp. 337–342).
14. Somaiah, K., Satish, P. V. V., Sunita, K., & Baratha Jyothi, N. (2015). Studies on the biochemical responses in the tissues of freshwater fish *Labeo rohita* exposed to the organophosphate, phenthoate.
15. Sultatos, L. G. (1998). Factors affecting the hepatic biotransformation of the phosphorothioate pesticide chlorpyrifos. *Toxicology, 51*, 191–200.
16. Susan, T. A., Sobha, K., Veeraiah, K., & Tilak, K. S. (2010). Studies on biochemical changes in the tissues of *Labeo rohita* and *Cirrhinus mrigala* exposed to fenvalerate technical grade.
17. Tripathi, G., & Verma, P. (2004). Endosulfan-mediated biochemical changes in the freshwater fish *Clarias batrachus*. *Biomedical and Environmental Sciences, 17*, 47–56.

A REVIEW OF BIVALVE DEPURATION: PRINCIPLES, SYSTEMS, AND TECHNICAL SPECIFICATIONS FOR SHELLFISH PURIFICATION

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Abstract

Bivalves are socio-economically vital aquatic mollusks characterized by their two-part hinged shells. As specialized filter feeders, they ingest organic matter alongside ambient waterborne pathogens, heavy metals, and biotoxins. To ensure food safety and meet commercial market standards, depuration—the process of purging contaminants in controlled, clean aquatic environments—is standard practice. This review examines the physiological mechanisms underlying bivalve depuration, details critical water quality parameters, contrasts flow-through versus recirculating systems, and provides comprehensive structural and operational blueprints for a standard commercial depuration facility. Finally, it addresses the fundamental advantages and biochemical limitations of this purification methodology.

1. Introduction to Bivalvia and Ecological Dynamics

A bivalve is an aquatic mollusk of the class Bivalvia, distinguished by a shell composed of two hinged halves, or "valves" (Gosling, 2015). These animals are found in diverse aquatic environments, often filter-feeding on plankton and other particles from the water using their specialized gills (Shumway, 2021). Famous examples of bivalves include clams, oysters, mussels, and scallops, which are important components of marine ecosystems and are widely consumed by humans. Individual species exhibit distinct morphological and behavioral adaptations to their specific substrates and ecological niches:

- **Oysters:** Some species permanently attach to hard substrates via cementation, remaining sessile throughout their adult lives (Galtsoff, 1964).
- **Mussels:** Mussels attach temporarily using byssus threads, a bundle of protein fibers that provides both structural security and flexible detachment options (Waite, 1983).
- **Clams:** Most clams are known for burrowing in sand or mud using a highly developed, muscular foot to escape predation (Ansell, 1962).
- **Scallops:** Scallops are another well-known type of bivalve, distinguished by their ability to swim freely via rapid valve clapping (Brand, 2016).

Bivalves are filter feeders in their feeding habit. During this process, they accumulate all suspended biological materials, including harmful microorganisms, heavy metals, and organic particles (Rippey, 1994). Before the product reaches the market, these materials have to be removed from their gut. The process of such purification is called depuration. Hence, depuration is the process of purification of shellfish in which the animals are placed in disinfected recirculating or running seawater and allowed to actively filter feed (Lee *et al.,* 2008). The process leads to the elimination of bacteria from the bivalve. Disinfection of circulating seawater can be achieved by the use of UV radiation, ozone treatment, irradiation, etc. (Guimarães Filho *et al.,* 2022). Quality of bivalve products that they import from markets to ascertain and maintain the quality of bivalve products depuration is essential. Simple depuration can be achieved by starving the bivalves in clean and filtered seawater or brackish water for a certain period of time. More effective depuration can be achieved by using disinfected water in the depuration process (Martinez-Albores *et al.,* 2020).

2. Mechanisms and Environmental Parameters of Depuration

Depuration leverages the shellfish's natural filter-feeding behavior. In a controlled environment, water quality parameters are optimized to encourage the animals to actively pump water, expel contaminants from their digestive tracts, and prevent recontamination (Richards, 1988). The baseline dynamics governing this metabolic purging rely on several interdependent factors:

- **Contaminants Targeted:** The primary goal is to remove bacteria and viruses, especially those associated with human sewage, such as *E. coli* and norovirus. While depuration is highly effective for bacteria, it is less reliable for removing certain viruses, marine biotoxins, or heavy metals, especially in highly contaminated shellfish (McLeod *et al.,* 2017).
- **Controlled Conditions:** The process takes place in a controlled facility with carefully maintained water quality. Critical parameters include:
    - **Temperature:** Kept within an optimal range (typically 14–29°C) to ensure the shellfish remain physiologically active and capable of rapid filtration (Guimarães Filho *et al.,* 2022).
    - **Salinity:** Must be consistent with the shellfish's original harvest environment to prevent osmotic shock and subsequent valve closure.
    - **Dissolved Oxygen:** Maintained at sufficient levels (typically over 5 ppm) for the shellfish to function normally.

- **Turbidity:** Kept low to prevent microorganisms from being shielded from sterilization systems and to prevent the re-ingestion of eliminated particulate waste.

2.1 Water Purification Technologies

The continuous sanitation of incoming or recirculating water supplies is mandatory to prevent cross-contamination. The primary technological methodologies deployed within modern processing contexts include:

- **Ultraviolet (UV) Irradiation:** The most common method in the U.S. and UK, it uses UV light to inactivate microorganisms by disrupting their nucleic acids without introducing chemical residuals into the system (Lees, 2000).
- **Ozonation:** Used widely in Europe, ozone gas disinfects the water efficiently due to its high oxidation potential, breaking down organic pollutants without leaving an off-taste in the shellfish (Schneider *et al.,* 2009).
- **Chlorination:** An older method that has fallen out of favor because it can inhibit the shellfish's pumping activity and alter the flavor, though it remains a highly economical solution for large-scale setups if carefully managed (Oliveira *et al.,* 2011).

3. Engineering Systems and Plant Specifications

Commercial facilities generally implement two hydraulic operational paradigms depending on geographic constraints and proximity to raw marine inputs (Lee *et al.,* 2008):

- **Flow-through Systems:** These are used when a facility is located near a reliable source of clean, high-quality seawater. The water is pumped in, filtered, treated, and passed through the tanks before being discharged.
- **Recirculating Systems:** These facilities recycle the tank water by passing it through sterilization and filtration equipment before returning it to the shellfish. They offer more control over water quality and reduce the risk of contaminants from the external environment entering the system.

3.1 Structural and Operational Requirements

For a standardized batch-process commercial depuration facility, the technical specifications are rigorously defined as follows:

- The basic principle for controlled depuration of bivalves involves providing clean and purified seawater in tanks, whereby the bivalves filter and pump such water for a period of 24 hours or more if required.
- Ideally, a depuration plant should be located near the least polluted source of water in the vicinity of bivalve farms. Also, the physical characteristics (salinity, temperature,

dissolved oxygen, etc.) of the seawater used in the depuration plant should not be radically different from that of the bivalve farming areas. Care should be taken such that the level of dissolved oxygen should not be allowed to drop below 2 mg/L.

- Two concrete seawater storage tanks of the dimension 20 × 8 × 8 m (total capacity 160 tonnes) should be constructed at a level above that of the depuration tank to facilitate gravity flow into the depuration tank. The water to be used will be first pumped into a rapid sand filter (preferably 2, arranged serially) to remove all suspended material.
- The choices for disinfection of seawater are chlorination, ozonation, and UV light irradiation. The latter two are expensive, and hence chlorination @ 3 ppm is the method chosen for this project design. After chlorinating for 12 hours, the water will be dechlorinated using vigorous aeration and/or neutralization with sodium thiosulphate for 12 hours.
- Most depuration plants use flow-through, once-through, or fill-and-draw principles. It is proposed here to use the batch process, wherein seawater is drawn from the supply, treated with a predetermined amount of disinfectant to reduce bacterial levels, stored for a time, and then pumped to the tank containing bivalves. The process will be repeated once to ensure complete depuration.
- Each depuration unit will consist of one concrete tank of the size 15 × 4 × 1 m with a gradient of 3% to hold bivalves. Bivalves will be placed in perforated plastic trays of standard size. The trays in a single tier will be raised from the tank bottom with the help of PVC pipe runners. The tank will have drain plugs at the lower end to facilitate cleaning and flushing.

3.2 Run Duration and Capacity Metrics

The dynamic metrics for maintaining standard operations dictate precise volumetric requirements per run cycle:

- **Duration of the Run:** 24 hours, executed in two cycles with one complete flushing for both mussels and oysters.
- **Total Holding Capacity:** 1.0 tonne of mussels and 0.62 tonnes of oysters per run.
- **Water Volume Requirement:** 144 m^3 of pre-treated seawater per run.

4. Advantages and Limitations of Depuration

4.1 Advantages

- **Reduces Pathogens:** It is highly effective at reducing bacteria like *E. coli* and improving the overall microbiological safety of the product (Rippey, 1994).

- **Maintains Freshness:** Because the shellfish remain alive throughout the process, their "live" or "fresh" status can be preserved, which is important for raw consumption channels.
- **Improves Quality:** Purging sand, silt, and other physical impurities makes the shellfish more palatable to consumers.
- **Expands Harvesting Areas:** It allows for the safe harvesting of shellfish from moderately polluted waters that would otherwise be off-limits for direct consumption markets (Oliveira *et al.,* 2011).

4.2 Limitations

- **Ineffective for High Pollution:** It is not a remedy for heavily contaminated shellfish from "prohibited" waters.
- **Not a Guarantee of Viral Safety:** While effective against bacteria, depuration can be less reliable for removing certain viruses, like norovirus and hepatitis A virus, as these can sometimes become tightly bound within the shellfish's tissues via specific ligands (McLeod *et al.,* 2017; Battistini *et al.,* 2021). Extended depuration periods at elevated temperatures are often required to achieve minor viral log reductions, making standard 24-42 hour commercial cycles inadequate for complete virological clearance (Rupnik *et al.,* 2021).
- **Limited Against Biotoxins and Chemicals:** It is not a reliable method for removing heavy metals or natural marine biotoxins that can cause shellfish poisoning, as these compounds are sequestered within fatty tissues and organs rather than free-floating in the lumen of the gut (Martinez-Albores *et al.,* 2020).
- **Requires Strict Controls:** The process requires careful monitoring and control of water parameters, and any disruption can compromise the effectiveness by causing the bivalves to cease pumping entirely.

References

1. Ansell, A. D. (1962). Observations on burrowing in the Veneridae (Bivalvia). *Biological Bulletin*, *123*(3), 521-530.
2. Battistini, R., Masotti, C., Listorti, V., Suffredini, E., Maurella, C., Garcia-Vozmediano, A., Costa, E., Iacona, F., Orlandi, M., Ercolini, C., & Serracca, L. (2021). Norovirus persistence in oysters to prolonged commercial purification. *Pathogens*, *10*(8), 944.
3. Brand, A. R. (2016). Scallop ecology: distributions and behavior. *Scallops: Biology, Ecology and Aquaculture*, *4*, 569-643.

4. Galtsoff, P. S. (1964). *The American Oyster: Crassostrea virginica Gmelin*. Fishery Bulletin of the Fish and Wildlife Service, Volume 64.
5. Gosling, E. (2015). *Bivalve Molluscs: Biology, Ecology and Culture*. John Wiley & Sons.
6. Guimarães Filho, C. E. F., Calixto, F. A. A., Kasnowski, M. C., & Mesquita, E. F. M. (2022). Depuration of bivalve molluscs: a literature review. *Food Science and Technology*, *42*, e06622
7. Lee, R., Lovatelli, A., & Ababouch, L. (2008). *Bivalve depuration: fundamental and practical aspects*. FAO Fisheries and Aquaculture Technical Paper, No. 511. Food and Agriculture Organization of the United Nations.
8. Lees, D. (2000). Viruses and bivalve shellfish. *International Journal of Food Microbiology*, *59*(1-2), 81-116.
9. Martinez-Albores, A., Lopez-Santamarina, A., Rodriguez, J. A., Ibarra, I. S., Mondragón, A. C., Miranda, J. M., Lamas, A., & Cepeda, A. (2020). Complementary methods to improve the depuration of bivalves: A review. *Foods*, *9*(2), 129.
10. McLeod, C., Polo, D., Le Saux, J. C., & Le Guyader, F. S. (2017). Depuration and relaying: A review on potential removal of Norovirus from oysters. *Comprehensive Reviews in Food Science and Food Safety*, *16*(4), 692-706.
11. Oliveira, J., Cunha, A., Castilho, F., Romalde, J. L., & Podani, J. (2011). Shellfish depuration. *Food Control*, *22*(8), 1109-1116.
12. Richards, G. P. (1988). Microbial purification of shellfish: a review of depuration and relaying. *Journal of Food Protection*, *51*(3), 218-251.
13. Rippey, S. R. (1994). Infectious diseases associated with the consumption of shellfish. *Clinical Microbiology Reviews*, *7*(4), 419-425.
14. Rupnik, A., Doré, W., Devilly, L., Fahy, J., Fitzpatrick, A., Schmidt, W., Hunt, K., Butler, F., & Keaveney, S. (2021). Evaluation of norovirus reduction in environmentally contaminated Pacific oysters during laboratory controlled and commercial depuration. *Food and Environmental Virology*, *13*(2), 229-240.
15. Schneider, K. R., Braddy, K. S., Rodrick, G. E., & Otwell, W. S. (2009). Ozone depuration of bivalve mollusks. *Ozone: Science & Engineering*, *31*(4), 307-314.
16. Shumway, S. E. (2021). *Shellfish Aquaculture and the Environment*. Wiley-Blackwell.
17. Waite, J. H. (1983). Quinone-tanned scleroproteins and bivalve byssus. *The Mollusca*, *1*, 467-504.

SHAPING THE FUTURE OF PHARMACEUTICALS:
THE STRATEGIC ROLE OF AI, MACHINE LEARNING, AND DATA SCIENCE

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Abstract

Artificial Intelligence and Data Science are reshaping the pharmaceutical sector by enhancing operational efficiency, lowering development expenses, speeding up drug discovery, and supporting personalized medical treatments. These advanced technologies are influencing every phase of the pharmaceutical process, including research, clinical testing, production, and patient management. In the coming years, the industry is expected to deliver more advanced medicines, quicker treatment solutions, and highly accurate healthcare services. At the same time, challenges related to ethics, patient data protection, and regulatory compliance must be addressed carefully to ensure secure and responsible use of these technologies. As AI technologies continue to advance, the pharmaceutical industry is likely to become more intelligent, technology-driven, and focused on improving patient outcomes.

Keywords: Artificial Intelligence, Data Science, Technologies, Pharma Industry

Introduction

The pharmaceutical industry has traditionally depended on time-consuming research procedures, costly clinical trials, and labor-intensive operations. Developing a single medicine often requires more than a decade of research and billions of dollars in investment. The emergence of Artificial Intelligence (AI) and Data Science is transforming this conventional system by enabling faster research processes, precision-based treatments, predictive analysis, and intelligent manufacturing methods. Artificial Intelligence refers to advanced computer systems designed to perform tasks that normally require human intelligence, including learning, reasoning, problem-solving, and decision-making.

Role of AI and Data Science in the Pharmaceutical Industry

1. Drug Discovery and Development

One of the most impactful applications of AI in pharmaceuticals is drug discovery and development. Traditionally, this process involves identifying disease targets, screening chemical compounds, conducting laboratory experiments, and performing clinical trials. These stages are often lengthy, expensive, and associated with high failure rates.AI technologies can rapidly analyze biological information, molecular structures, and scientific literature, significantly accelerating the discovery process.

Benefits

- Faster identification of potential drug candidates
- Reduction in research and development expenses
- Improved prediction of drug effectiveness
- Lower risk of failure during clinical trials

2. Personalized Medicine

AI and Data Science support personalized or precision medicine by examining genetic information, patient lifestyles, medical records, and treatment responses. This allows healthcare professionals to design therapies tailored to individual patient needs.

Advantages

- Improved treatment effectiveness
- Fewer side effects
- More accurate diagnoses
- Customized therapeutic solutions

This approach is particularly valuable in cancer treatment, where therapies can be developed according to a patient's genetic profile.

3. Clinical Trial Optimization

Clinical trials are essential for testing the safety and effectiveness of medicines, but they are often expensive and time-consuming. AI improves the efficiency of clinical trials by assisting with patient recruitment, monitoring participant responses, identifying suitable candidates, and predicting trial outcomes.

Future Impact

- Faster drug approval processes
- Reduced operational costs
- Enhanced patient safety monitoring
- Improved participant retention rates

4. Predictive Analytics in Healthcare

Data Science enables pharmaceutical companies to forecast disease outbreaks, estimate drug demand, evaluate treatment performance, and detect adverse drug reactions. Predictive analytics helps organizations make informed healthcare and business decisions.

Applications

- Epidemic prediction
- Inventory and supply management
- Risk evaluation
- Preventive healthcare planning

5. AI in Manufacturing and Supply Chain Management

AI-powered automation is improving pharmaceutical manufacturing and logistics. Intelligent systems can monitor equipment performance, optimize production processes, ensure quality control, and improve supply chain forecasting.

Benefits

- Reduction in human errors
- Lower manufacturing costs
- Enhanced product quality
- Faster distribution of medicines

6. Drug Repurposing

AI can also help identify existing medicines that may be effective for treating different diseases. This approach gained significant importance during the COVID-19 pandemic, where researchers used AI tools to analyze existing drugs for potential treatment options.

Advantages

- Faster development timelines
- Lower research expenses
- Rapid response during health emergencies

7. Virtual Health Assistants and Chatbots

AI-based virtual assistants and chatbots support patients by providing medication reminders, answering healthcare-related questions, scheduling appointments, and tracking symptoms. These technologies improve patient engagement, accessibility, and healthcare communication.

3. Clinical Trial Optimization

Clinical trials are essential for testing the safety and effectiveness of pharmaceutical products, but they often require substantial time and financial investment. AI technologies are improving the efficiency of clinical trials by enhancing patient recruitment, monitoring participant health, and predicting trial performance.AI systems can evaluate medical histories and genetic information to identify suitable candidates for clinical studies. This reduces delays associated with patient enrollment and improves trial success rates.

Additional AI capabilities include:

- Monitoring patient medication compliance
- Detecting side effects at an early stage
- Predicting participant dropout risks
- Automating clinical data analysis

Benefits

- Quicker completion of clinical studies
- Reduced operational costs
- Improved patient protection
- Higher accuracy in clinical data management

4. Predictive Analytics in Healthcare

Predictive analytics combines AI and Data Science to forecast future healthcare events using historical and real-time information. Pharmaceutical companies and healthcare institutions use predictive models to improve medical decision-making and healthcare planning.

AI systems can estimate:

- Disease outbreak patterns
- Medication demand
- Hospital readmission probabilities
- Potential adverse drug reactions
- Treatment success rates

5. AI in Manufacturing and Supply Chain Management

Artificial Intelligence is modernizing pharmaceutical manufacturing and supply chain operations through automation, intelligent monitoring, and real-time analysis. Pharmaceutical organizations use AI systems to improve production efficiency, maintain medicine quality, and optimize inventory control. Machine learning tools can analyze production data to identify equipment failures, detect manufacturing defects, and ensure compliance with regulatory standards.

Applications

- Automated product quality inspection
- Optimization of manufacturing processes
- Inventory and demand forecasting
- Intelligent packaging systems
- Supply chain monitoring and risk management

Robotic systems powered by AI are increasingly used in pharmaceutical factories to perform repetitive and precision-based tasks.

Advantages

- Reduction in manual errors
- Faster manufacturing operations
- Lower operational costs
- Improved product consistency and safety
- Efficient medicine distribution systems

Expansion of AI and Data Science in Australia

Australia considers Artificial Intelligence a key technology for future economic progress and international competitiveness. To support innovation and commercialization, the Australian government has introduced several national strategies, investment programs, and research initiatives focused on AI and Data Science development.

- Establishing a strong national AI research environment
- Promoting partnerships between universities and industries
- Supporting technology startups and innovation centers
- Encouraging ethical and responsible AI development
- Enhancing workforce digital skills and technical education

Australia is also emphasizing the development of AI systems that are transparent, reliable, secure, and socially beneficial.

Research Areas in Australia

1. Healthcare and Medical Innovation

Australia is making significant progress in AI-driven healthcare research. Artificial Intelligence and Data Science technologies are helping healthcare professionals, scientists, and pharmaceutical organizations improve diagnosis, treatment, and patient management.

Applications

- Medical imaging analysis
- Early cancer detection
- Precision healthcare
- Genomic studies
- Remote healthcare monitoring
- Robot-assisted surgery

Researchers in Australia are using machine learning systems to analyze large healthcare datasets and identify disease patterns more efficiently. AI tools are also supporting the early diagnosis of chronic illnesses such as diabetes, cancer, and cardiovascular diseases.

Pharmaceutical Research

Australian research institutions are applying AI technologies in:

- Medicine discovery and development
- Optimization of clinical trials
- Predictive healthcare analysis
- Personalized treatment planning

2. Artificial Intelligence in Agriculture

Agriculture is a major contributor to Australia’s economy, and AI technologies are improving agricultural productivity and environmental sustainability.

AI Applications in Farming

- Intelligent irrigation systems
- Prediction of crop diseases
- Soil quality monitoring
- Livestock tracking technologies
- Automated harvesting equipment
- Climate and weather forecasting

3. Mining and Industrial Automation

Australia is internationally recognized for its mining industry, and AI technologies are transforming mining operations through automation and predictive analytics.

Applications

- Autonomous mining vehicles
- Prediction of equipment failures
- Workplace safety monitoring
- Mineral exploration systems
- Smart transportation and logistics

Mining organizations are using robotics and machine learning systems to improve operational efficiency and worker safety.Australia continues to invest in advanced cybersecurity technologies to protect businesses, government systems, and essential national services.

6. Environmental and Climate Studies

Australia is applying AI and Data Science technologies to address environmental challenges and climate-related issues.

Applications

- Bushfire prediction systems
- Climate modeling and forecasting
- Wildlife protection and monitoring
- Water management solutions
- Renewable energy optimization

AI technologies analyze satellite images, environmental data, and weather patterns to support disaster management and sustainability initiatives.

Benefits

- Better environmental monitoring
- Faster emergency response systems
- Improved conservation planning
- Sustainable use of natural resources

AI-supported climate research is helping Australia prepare for extreme weather events and environmental threats.

Australian Universities and Research Organizations

Several Australian universities and research organizations are internationally recognized for their contributions to AI and Data Science research.

Leading Institutions

- The University of Melbourne
- The Australian National University
- The University of Sydney
- Monash University
- The University of Queensland
- CSIRO (Commonwealth Scientific and Industrial Research Organisation)

These institutions conduct advanced studies in:

- Machine learning
- Robotics and automation
- Natural Language Processing
- Data analytics
- Healthcare AI technologies
- Quantum computing

AI Ethics in Australia

Australia strongly emphasizes:

- Fair and unbiased AI systems
- Transparent automated decision-making
- Protection of personal information
- Accountability in AI operations

Challenges Facing Australia

Although Australia has made remarkable progress, several challenges remain in AI and Data Science advancement.

Skills and Workforce Gap

There is increasing demand for professionals with expertise in:

- Artificial Intelligence
- Machine learning
- Data analytics
- Cybersecurity
- AI engineering

Data Privacy Issues

Protecting sensitive healthcare, financial, and personal data remains a significant challenge.

High Infrastructure Expenses

Advanced AI research requires costly computing systems, cloud technologies, and digital infrastructure.

Ethical and Legal Concerns

Balancing technological innovation with ethical standards and legal regulations continues to be important.

Future of AI and Data Science in Australia

Australia is expected to become a major international center for AI innovation and scientific research in the coming decades.

Recent Advances in AI and Data Science Research in Leading Australian Institutions

1. The University of Melbourne

The University of Melbourne is widely recognized as one of Australia's top institutions for Artificial Intelligence and Data Science research. It emphasizes interdisciplinary studies combining AI with healthcare, engineering, environmental science, and business analytics.

Recent Developments

The university has strengthened its Data Science programs, focusing on large-scale data processing, machine learning techniques, and advanced statistical modeling. In recent years, particularly around 2026, the Faculty of Medicine, Dentistry and Health Sciences introduced AI-focused training workshops to help researchers apply intelligent systems in biomedical studies, clinical research, and scientific writing.

Researchers are actively applying AI technologies in:

- Medical diagnosis and imaging
- Genomic and genetic research
- Predictive healthcare modeling
- Environmental and climate analysis

Research Areas

- Machine Learning and Artificial Intelligence
- Big Data Analytics
- Healthcare and Medical AI
- Bioinformatics
- AI Ethics and Governance
- Statistical and Computational Science

Institutional Strengths

- Strong interdisciplinary collaboration across science, medicine, and engineering
- Advanced facilities for biomedical and computational research
- Strong partnerships with industry and healthcare organizations

2. The Australian National University (ANU)

The Australian National University is globally respected for its advanced research in Artificial Intelligence, robotics, machine learning, and computer vision.

Recent Developments

ANU has engaged in international collaborations to enhance AI research capabilities. In 2026, it partnered with AI research organizations to strengthen AI applications in science and healthcare, particularly in analyzing genetic data and improving rare disease diagnosis. The university has also supported innovation in AI hardware through startup initiatives focused on next-generation computing technologies, including chip design for faster and more efficient AI processing. Additionally, collaborations with global technology companies have supported research in:

- Robotics and intelligent systems
- Natural language processing
- Formal verification and system reliability
- AI curriculum development

ANU researchers are also advancing computer vision systems that improve machine understanding of visual data while reducing algorithmic bias.

Research Areas

- Artificial Intelligence and Machine Learning
- Robotics and Intelligent Systems
- Computer Vision
- AI Planning and Decision Systems
- Quantum Computing

3. The University of Sydney

The University of Sydney is actively involved in cutting-edge research in AI hardware, medical intelligence, robotics, and data-driven innovation.

Recent Developments

Researchers have made progress in developing advanced computing technologies, including photonic-based AI chips that use light instead of traditional electrical signals. This innovation has the potential to significantly enhance processing speed while reducing energy consumption in AI systems.

Research Areas

- AI Hardware and Systems Engineering
- Quantum Computing Technologies
- Medical and Healthcare AI
- Robotics and Automation
- Data Science and Analytics
- Smart Infrastructure Development

Research Contributions

- Energy-efficient AI computing systems
- AI applications in medical diagnosis and healthcare
- Smart city and transport innovation solutions

4. Monash University

Monash University is a major contributor to AI research in cybersecurity, healthcare analytics, deep learning, and intelligent systems.

Recent Research Focus

Researchers at Monash are working on multiple AI-driven solutions, including:

- AI-based medical imaging systems
- Intelligent transport and mobility systems
- Detection of deepfakes and digital manipulation
- Smart industrial and manufacturing systems
- AI-based public health analytics

The university has also received support from national research funding programs focused on cybersecurity, artificial intelligence, and advanced computing systems.

Research Areas

- Deep Learning and Neural Networks
- Cybersecurity and AI Safety
- Medical Informatics
- Data Engineering
- Autonomous and Intelligent Systems
- Human-Centered AI

5. The University of Queensland (UQ)

The University of Queensland is well known for its research in AI applications related to healthcare, agriculture, environmental science, and robotics.

Research Activities

UQ researchers are developing intelligent systems for:

- Environmental monitoring and sustainability
- Agricultural automation and precision farming
- Disease prediction and healthcare analytics
- Personalized medicine and treatment planning
- Climate modeling and environmental forecasting

The university is also exploring integration of AI with robotics and Internet of Things (IoT) technologies to improve industrial automation and healthcare delivery.

Research Areas

- Agricultural Artificial Intelligence
- Environmental Data Science
- Healthcare Analytics and Bioinformatics
- Robotics and Intelligent Automation
- Sustainability-focused AI systems

Australian Pharmaceutical Industry

1. Market size & expected growth

The Australian pharmaceutical sector is currently valued at approximately USD 36–37 billion (2025). It is projected to grow to around USD 60+ billion by 2033, reflecting a compound annual growth rate (CAGR) of roughly 6–7%. The industry is already well-established and is expected to nearly double in size over the next decade, driven by rising healthcare demand and innovation in medicines.

2. Pharmaceutical manufacturing outlook

Pharmaceutical production within Australia is expanding at a faster pace than overall drug consumption. Estimated growth: ~USD 4.3 billion (2023) → ~USD 9+ billion by 2030 Growth rate: ~11–12% CAGR.

Manufacturing growth:

- Increased focus on domestic production and supply security
- Expansion of biotech and advanced therapies
- Post-COVID restructuring of global supply chains

3. Major growth drivers

Ageing population

Australia’s growing elderly population is increasing demand for:

- Chronic disease treatments
- Cancer therapies
- Cardiovascular medicines

Conclusion

Despite the remarkable advancements in artificial intelligence (AI) and data science, several challenges must be addressed before their full potential can be realized in the pharmaceutical sector. Ensuring the privacy and security of sensitive patient data remains a major concern, as AI systems require access to large volumes of clinical and genetic information. Ethical issues related to AI-driven decision-making, including transparency, accountability, and informed consent, also require careful consideration. Another significant challenge is the presence of bias in training datasets, which can lead to inaccurate predictions and unequal healthcare outcomes across different populations. Furthermore, the implementation of AI technologies demands substantial financial investment in infrastructure, computational resources, and skilled personnel. The absence of comprehensive and harmonized regulatory frameworks for AI-based pharmaceutical applications also creates uncertainty regarding validation, approval, and clinical adoption.

Looking ahead, AI is expected to serve as a powerful decision-support tool for scientists engaged in drug discovery and development rather than replacing human expertise. Data science will become a cornerstone of healthcare innovation by enabling evidence-based decision-making and predictive modeling. Pharmaceutical companies will increasingly adopt automation, machine learning, and predictive analytics to accelerate research, optimize clinical trials, and improve manufacturing processes. Overall, AI and data science are poised to transform the pharmaceutical industry by making drug development faster, more cost-effective, and increasingly focused on personalized and precision healthcare solutions.

References

1. Suri, G. S., *et al.* (2024). Beyond boundaries: Exploring the transformative power of AI in pharmaceuticals. *Discover Artificial Intelligence*. https://doi.org/10.1007/s44163-024-00192-7
2. Kant, S., *et al.* (2025). Artificial intelligence in drug discovery and development: Transforming challenges into opportunities. *Discover Pharmaceutical Sciences*. https://doi.org/10.1007/s44395-025-00007-3
3. Saini, J. P., *et al.* (2025). AI-driven innovations in pharmaceuticals: Optimizing drug discovery and industry operations. *European Journal of Pharmaceutical Sciences*. https://doi.org/10.1016/j.ejps.2024.106938

4. *Artificial intelligence in pharmaceutical sciences: A comprehensive review*. (2025). *Medical & Novel Therapeutics*. https://doi.org/10.1016/j.medntd.2025.100375
5. *Harnessing the power of artificial intelligence in pharmaceuticals: Current trends and future prospects*. (2025). *Intelligent Pharmacy*. https://doi.org/10.1016/j.ipha.2024.12.001
6. Somara, S., *et al.* (2025). Artificial intelligence in biotechnology and pharmaceuticals: Evolution, applications, and regulatory frontiers. *Current Stem Cell Reports*. https://doi.org/10.1007/s40778-025-00249-y
7. Blanco-Gonzalez, A., *et al.* (2022). The role of AI in drug discovery: Challenges, opportunities, and strategies. *arXiv*. https://arxiv.org/abs/2212.08104
8. Han, Y., & Tao, J. (2024). Revolutionizing pharma: AI and LLM trends in pharmaceutical industry. *arXiv*. https://arxiv.org/abs/2401.10273
9. Zielinski, A. (2021). AI and the future of pharmaceutical research. *arXiv*. https://arxiv.org/abs/2107.03896
10. Morgan, S., *et al.* (2008). Balancing health and industrial policy objectives in the pharmaceutical sector: Lessons from Australia. *Health Policy, 87*(2), 133–145. https://doi.org/10.1016/j.healthpol.2008.01.003
11. Doran, E., & Henry, D. (2008). Australian pharmaceutical policy: Price control, equity, and drug innovation in Australia. *Journal of Public Health Policy, 29*(1), 106–120. https://doi.org/10.1057/palgrave.jphp.3200170
12. Tirrell, Z., *et al.* (2026). Accessing the risks: A mixed methods study of risk management in Australian pharmaceutical market access. *Health Policy, 168*, 105608. https://doi.org/10.1016/j.healthpol.2026.105608
13. Fabbri, A., *et al.* (2019). Pharmaceutical industry funding of health consumer groups in Australia: A cross-sectional analysis. *International Journal of Health Services*. https://doi.org/10.1177/0020731418823376

A CRITICAL REVIEW OF TRADITIONAL KNOWLEDGE SYSTEMS IN WETLAND CONSERVATION AND MANAGEMENT

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Abstract

Wetlands are among the most productive ecosystems on Earth, providing essential ecological services such as biodiversity conservation, water purification, flood regulation, carbon sequestration, and livelihood support. However, rapid urbanization, agricultural expansion, industrial development, climate change, and unsustainable resource use have accelerated wetland degradation worldwide. Traditional Knowledge Systems (TKS), also known as Traditional Ecological Knowledge (TEK), developed and transmitted across generations by indigenous and local communities, offer valuable insights into the sustainable management and conservation of wetland ecosystems. These knowledge systems encompass practices related to water resource management, sustainable agriculture, fisheries, medicinal plant conservation, weed control, and biodiversity protection. Despite their proven effectiveness, many modern conservation policies rely primarily on centralized management approaches, often overlooking the participation and knowledge of local communities. This exclusion has weakened community stewardship and contributed to ecological degradation. This review critically examines the role of Traditional Knowledge Systems in wetland conservation and management by synthesizing recent literature on traditional practices, their ecological significance, and their integration with contemporary scientific approaches. It highlights successful case studies, identifies existing challenges, and discusses opportunities for combining indigenous knowledge with modern technologies and policy frameworks. Integrating traditional wisdom with scientific innovation can strengthen ecosystem resilience, promote sustainable resource management, and support long-term conservation of wetlands while ensuring social equity and community participation.

Keywords: Traditional Knowledge Systems, Traditional Ecological Knowledge, Wetland Conservation, Indigenous Knowledge, Sustainable Resource Management, Biodiversity Conservation, Community-Based Management.

1. Introduction and Ecological Status of Indian Wetlands

Wetlands are critical socio-economic and ecological assets that regulate climate, control floods, purify water, and support vast biodiversity. Historically, India has a rich lineage of communitydriven wetland protection. A prominent historical manifestation includes building forts strategically around water features to harvest monsoon rainfall and provide structural cooling during arid periods. Similarly, the construction of artificial wetlands has long served as a safe haven for maintaining regional avian biodiversity.

Despite their importance, modern floodplains and coastal wetlands face severe deterioration due to rapid industrialization, climate change, and uncoordinated policy execution. Bridging modern geospatial monitoring tools with age-old communal wisdom is increasingly recognized as the primary mechanism for restoring ecosystem equilibrium.

2. Methodological Approach (PRISMA Framework)

To systematically eliminate publication bias, recent literature uses structured protocols modeled after the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Qualitative synthesis methodologies typically draw from extensive multidisciplinary databases (e.g., Scopus, ScienceDirect, Web of Science, Google Scholar, and ShodhGanga). Search criteria focus on intersecting terms such as "wetland conservation," "indigenous practices," and "sustainable resource management". For instance, out of an initial pool of over 160 records, rigorous screening for eligibility commonly narrows comprehensive qualitative evaluations down to approximately 60–68 core peer-reviewed studies.

3. Key Domains of Traditional Knowledge Systems (TKS)

A. Traditional Agricultural Systems

Indigenous agricultural techniques balance food production with ecosystem protection through crop diversification, organic farming, and highly adaptive irrigation strategies. In Eastern India, combining traditional rice cultivation practices—such as the System of Rice Intensification (SRI)—with native wetland hydrology optimizes crop yields while minimizing environmental pollution. Furthermore, traditional weed management completely circumvents synthetic chemical use. Local communities utilize manual weeding, planned crop rotation, and native herbal extracts to safely regulate weed infestations, ensuring that runoff does not degrade local water quality or harm aquatic biodiversity.

B. Sustainable Traditional Fisheries

Traditional fishing practices prioritize the long-term viability of fish stocks over short-term exploitation. Guided by deep-rooted cultural beliefs, myths, and taboos, local communities selfregulate harvests using seasonal fishing bans and protecting critical fish breeding grounds.

Communities employ selective, low-impact artisanal gear constructed from natural materials—such as bamboo traps, specific gill nets, and seines—which drastically minimize non-target bycatch and prevent structural habitat disturbance. Additionally, studies show that traditional community-based fishing festivals and sustained artisanal activities dynamically balance open waters, significantly enhancing the distribution and abundance of wetland bird species.

C. Ethnobotanical Knowledge and Wetland Plants

Local communities possess an advanced ethnobotanical understanding of wetland flora. Native vegetation acts as a natural engine for sediment stabilization, erosion control, and biopurification. Furthermore, communities manage these landscapes sustainably due to their reliance on "cultural keystone species" for medicine, construction, and livelihoods. Indigenous groups utilize wetland plants like *Commelina latifolia*, *Ageratum conyzoides*, *Persicaria decipiens*, and various *Cyperus* (sedge) species to treat complex ailments ranging from stomach disorders and respiratory issues to fever and skin infections. Protecting this plant diversity ensures both ecosystem resilience and the preservation of irreplaceable cultural heritage.

4. Policy Integration: Global and National Frameworks

Modern conservation policies emphasize merging international mandates with localized community execution.

- **International Frameworks:** The Ramsar Convention (1971) explicitly mandates integrating socio-economic, cultural-spiritual, and traditional knowledge into wetland management. This is evident in countries like Australia, where the government's *Working on Country* program provides paid employment to Indigenous Australians to manage expansive Indigenous Protected Areas. Similarly, the Convention on Biological Diversity (CBD) and UNESCO’s Man and the Biosphere Programme actively leverage community-led initiatives to restore designated World Heritage ecosystems.
- **National Initiatives (India):** Following India’s 1982 ratification of the Ramsar Convention, the Ministry of Environment, Forest, and Climate Change (MoEFCC) instituted the National Wetlands Conservation Programme (NWCP) in 1986 and the National Lake Conservation Plan (NLCP) in 2001. These legislative frameworks dictate stakeholder engagement, relying heavily on partnerships between State Wetland Authorities, non-governmental organizations (such as WWF-India and Wetlands International South Asia), and indigenous communities to execute site-specific management and monitoring protocols.

Conclusion

Integrating Traditional Knowledge Systems into modern environmental engineering and conservation paradigms is highly effective. Moving away from strictly exclusionary government controls toward participatory, community-led stewardship ensures sustainable resource extraction, preserves cultural identity, and strengthens the climate resilience of fragile wetland ecosystems.

References

1. Anderson, M. K. (2005). *Indigenous knowledge and biodiversity conservation: From recognition to application.*
2. Barman, A., Rajak, F., & Jha, R. (2025). Integrating traditional knowledge systems for wetland conservation and management: A critical analysis. *Nature Environment and Pollution Technology, 24*(1), B4212.
3. Berkes, F. (1999). *Sacred ecology: Traditional ecological knowledge and resource management.*
4. Boru, W., *et al.* (2024). Ethnobotanical study of medicinal plants used by local communities in Southeast Ethiopia. *Journal of Ethnobiology and Ethnomedicine.*
5. Chaudhary, R., *et al.* (2017). Traditional weed management practices in wetland conservation: Lessons from India. *Ecology and Environment.*
6. Davidson-Hunt, I., & Berkes, F. (2003). Learning as you journey: Anishinaabe perception of social-ecological environments and adaptive learning. *Ecology and Society.*
7. Gadgil, M., & Berkes, F. (1991). Traditional resource management systems. *Resource Management and Optimization, 8*(3–4), 127–141.
8. Garg, J. K., *et al.* (2015). Wetland conservation and management in India using geospatial techniques. *Remote Sensing Applications.*
9. Gupta, S., *et al.* (2018). Traditional agricultural practices in wetland conservation: A case study from India. *Journal of Sustainable Agriculture.*
10. Huntington, H. P. (2000). Using traditional ecological knowledge in science: Methods and applications. *Ecological Applications.*
11. Mishra, A., & Behera, B. (2019). Indigenous fishing methods for wetland conservation: A case study from India. *International Journal of Fisheries and Aquatic Studies.*
12. Mohanty, S., *et al.* (2021). Role of traditional agriculture in wetland conservation: A case study from eastern India. *Journal of Agriculture and Rural Development.*

13. Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine, 6*(7), e1000097.
14. Newmaster, S. G., *et al.* (2011). Traditional ecological knowledge (TEK) of seagrasses in coastal communities. *Biological Conservation.*
15. Panigrahy, S., *et al.* (2012). National wetland inventory and assessment (NWIA) in India. *Environmental Monitoring and Assessment.*
16. Patel, K., *et al.* (2018). Traditional fishing techniques in wetland conservation: A review. *Journal of Experimental Zoology.*
17. Ramsar Convention. (1971). *Strategic framework and guidelines for the future development of the List of Wetlands of International Importance.*
18. Sabola, C., *et al.* (2007). Use of indigenous knowledge and traditional practices in fisheries management: A case of Chisi Island, Lake Chilwa. *Malawi Journal of Science.*
19. Sharma, P., & Das, R. (2019). Conservation implications of traditional fishing practices in wetlands. *Wetlands Ecology and Management.*
20. Singh, R., *et al.* (2020). Indigenous farming techniques for wetland conservation in India: A review. *Journal of Environmental Science and Health.*
21. Sundar, K. G., & Kittur, S. (2013). Can wetlands maintained for human use also help conserve biodiversity? *Biological Conservation, 168*, 49–56.
22. Turner, N. J., Ignace, M. B., & Ignace, R. (2000). Cultural keystone species: Implications for ecological conservation and restoration. *Ecology and Society, 4*(1).

PRECISION AQUACULTURE AND SMART FISH FARMING: INTEGRATING DIGITAL TECHNOLOGIES FOR SUSTAINABLE AQUATIC FOOD SYSTEMS

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Abstract

Precision aquaculture represents a paradigm shift in the global seafood industry, applying sensor networks, machine learning, computer vision, robotics, and real-time data analytics to optimise the production of aquatic organisms. This chapter provides a comprehensive examination of the foundational concepts, enabling technologies, and practical implementations of smart fish farming. Beginning with the ecological and economic pressures driving innovation, the chapter proceeds through water quality automation, AI-driven feeding systems, genomic breeding tools, digital twin modelling, and the logistical challenges of deploying such systems across diverse cultural and geographic contexts. Evidence drawn from peer-reviewed literature, industrial deployments, and emerging policy frameworks is synthesised to provide practitioners and researchers with an actionable understanding of where the field stands and where it is heading.

Keywords: Precision Aquaculture, Smart Fish Farming, IoT, Machine Learning, Water Quality Monitoring, Automated Feeding, Digital Twin, Sustainable Aquaculture.

1. Introduction

The global demand for seafood has grown relentlessly over the past five decades. The Food and Agriculture Organization of the United Nations projects that aquaculture must supply more than 60% of human seafood consumption by 2030 to compensate for the stagnation of wild-catch fisheries (1). Meeting this target while simultaneously reducing the sector's ecological footprint — including nutrient discharge, antibiotic use, and land-use conversion — demands a fundamental rethinking of how fish are farmed.

Precision aquaculture emerged in the early 2010s as an analogue to precision agriculture, adapting the core philosophy of site-specific management to the aquatic environment. Where precision agriculture applies variable-rate inputs across heterogeneous land surfaces, precision aquaculture applies adaptive management decisions across heterogeneous aquatic conditions — conditions that can change within minutes as temperature, dissolved oxygen, pH, and biological oxygen demand shift in response to stocking density, feeding schedules, weather, and microbial activity (2). The difficulty of this challenge is compounded by the opacity of water: unlike a field crop, fish cannot be directly observed without specialist imaging equipment, making behavioural and physiological data collection inherently indirect (3).

The digitisation of aquaculture infrastructure — encompassing sensor networks, the Internet of Things (IoT), cloud computing, edge processing, computer vision, and artificial intelligence (AI) — has created an opportunity to close this observational gap. Smart fish farming systems can now monitor hundreds of environmental and biological variables continuously, feed the resulting data streams into predictive models, and trigger automated interventions faster and more precisely than any human operator could achieve (4). The economic incentives are substantial: studies across Atlantic salmon, tilapia, and shrimp farms have demonstrated feed conversion ratio (FCR) improvements of 10–25%, mortality reductions of 15–30%, and labour cost savings exceeding 40% following the deployment of smart monitoring and automated feeding systems (5, 6).

2. Conceptual Evolution of Precision Aquaculture

2.1 From Traditional to Data-Driven Farming

Traditional aquaculture is characterised by periodic manual observation, fixed feeding schedules, and reactive rather than proactive management. Farmers typically check water parameters once or twice daily, adjust feeding rates on the basis of visual estimates of fish appetite, and respond to disease outbreaks after clinical signs have already manifested. This reactive model results in suboptimal resource utilisation and elevated biological risk (7).

The first generation of aquaculture automation — appearing in the 1980s and 1990s — introduced mechanical feeders, basic aeration timers, and alarm-based dissolved oxygen (DO) monitors. These systems reduced labour but remained essentially open-loop: they delivered fixed inputs on a schedule rather than responding dynamically to real conditions. The conceptual leap to precision aquaculture required the convergence of three developments: (i) affordable, robust multi-parameter sensors capable of continuous submersible operation; (ii) wireless communication infrastructure, including cellular and satellite networks; and (iii) machine learning algorithms capable of finding actionable patterns in large, noisy, temporally structured datasets (8).

2.2 Defining Precision Aquaculture

A widely cited working definition holds that precision aquaculture is "the application of information technologies to measure, interpret, and respond to spatio-temporal variability in aquatic production environments and in the organisms, they contain, with the aim of optimising productivity, quality, welfare, and environmental performance" (2). This definition highlights four key attributes: (i) the centrality of measurement; (ii) the need for interpretation; (iii) the requirement for active response mechanisms; and (iv) a multi-objective performance framework extending beyond yield alone.

3. Real-Time Water Quality Monitoring Systems

3.1 The Primacy of Water Quality

Water is the medium through which all biological processes in aquaculture occur. Temperature governs metabolic rate and feed conversion; DO determines aerobic capacity and stress susceptibility; pH influences nitrification efficiency and gill function; ammonia and nitrite concentrations reflect waste accumulation; salinity affects osmoregulatory energy expenditure; and turbidity signals particulate load that can impair feeding behaviour (10). The interactive effects of these parameters are non-linear: a temperature increase of 2°C can halve the DO saturation point, simultaneously elevate metabolic oxygen demand and reducing oxygen availability — a critical combination in high-density systems (11).

Table 1: Key water quality parameters monitored in precision aquaculture systems, with target ranges, required sensor accuracy, and management significance

Parameter	Optimal Range	Sensor Accuracy	Biological Significance	Management Note
Temperature (°C)	8–22 (salmon)	< ±1°C / hr	Metabolic rate, FCR, DO solubility	High priority: drives all downstream parameters
Dissolved Oxygen (mg/L)	> 7 (critical)	< 0.3 mg/L	Aerobic metabolism, stress threshold	Most common trigger for emergency aeration
pH	6.5–8.5	< 0.2 units	Gill function, nitrification	Interacts nonlinearly with ammonia toxicity
Total Ammonia-N (mg/L)	< 0.5 (TAN)	< 0.05 mg/L	Gill damage, immune suppression	Toxicity pH-dependent (un-ionised fraction)
Salinity (ppt)	Species-specific	< 1 ppt	Osmoregulatory energy cost	Critical at smoltification in salmon
Turbidity (NTU)	< 20 (typical)	< 2 NTU	Feeding behaviour, UV steriliser eff.	Elevated after storms or algal blooms

Given this complexity, single-parameter monitoring is insufficient for precision management. Modern smart farms deploy multi-parameter sondes — integrated sensor assemblies capable of simultaneously measuring eight to fifteen variables at sampling intervals of one to fifteen minutes — at multiple depths and locations within each production unit (12).

3.2 Sensor Technologies

Electrochemical sensors remain the workhorse of aquaculture water quality monitoring. Polarographic and galvanic DO sensors, ion-selective electrodes for pH and specific ions, and conductivity cells for salinity estimation have improved markedly in drift stability and fouling resistance since the early 2000s (13). Optical sensors — particularly luminescence-based DO sensors and fluorometric sensors for chlorophyll and turbidity — offer reduced maintenance requirements because they lack membranes susceptible to biofouling (14).

3.3 IoT Architectures and Edge Computing

The data volumes generated by dense sensor networks necessitate careful architectural choices. Three-tier IoT architectures, comprising sensor nodes, edge gateways, and cloud platforms, are now the standard approach in commercial deployments (17). Edge gateways perform local preprocessing, anomaly detection, and alarm generation, ensuring that critical events trigger responses within seconds even when cloud connectivity is interrupted (18). Figure 1 illustrates the complete three-tier architecture with data-flow directions.

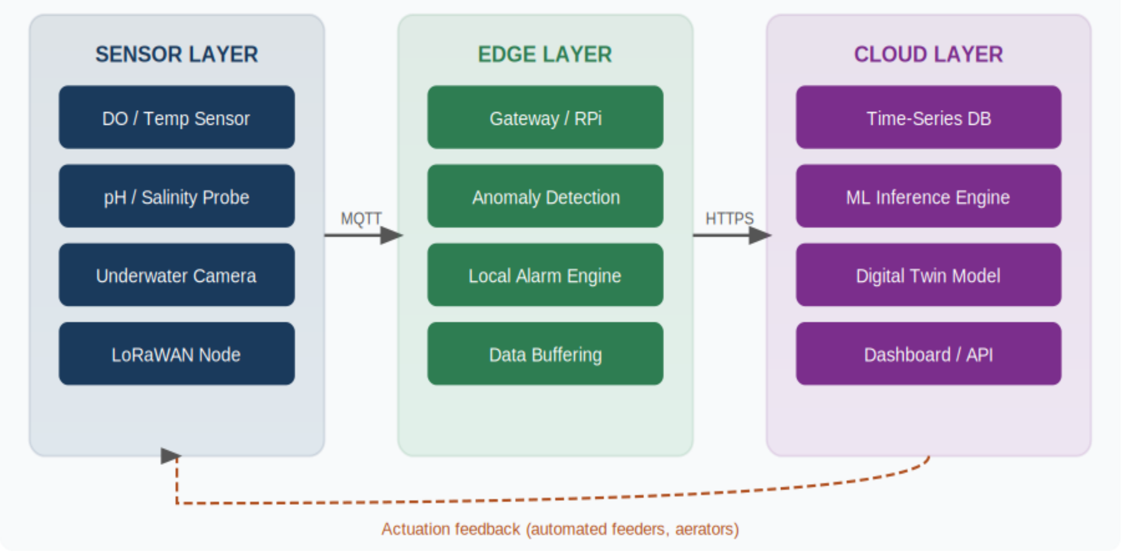

Figure 1: Three-tier IoT architecture for precision aquaculture: sensor layer, edge gateway layer, and cloud analytics layer, with actuation feedback loop

3.4 Predictive Water Quality Modelling

Recurrent neural networks — particularly long short-term memory (LSTM) architectures — have demonstrated superior performance for multi-step-ahead DO and temperature forecasting relative to traditional autoregressive models (21). A systematic review by Shi et al. (22) found that LSTM-based models achieved mean absolute errors below 0.3 mg/L for 24-hour-ahead DO forecasting across five independent salmon and shrimp datasets. Such forecasts enable pre-emptive aeration, feeding reduction, or harvest decisions that prevent the accumulation of physiological stress rather than merely responding to it.

4. Artificial Intelligence in Feeding Management and Biomass Estimation

4.1 The Feed Optimisation Problem

Feed represents 40–70% of the variable operating cost in most intensive aquaculture systems, and uneaten feed is the single largest source of nutrient pollution in pen-based salmon and trout farming (23). Optimal feeding — delivering exactly the amount of feed that fish will consume at any given moment — is therefore both the most economically significant and the most ecologically important management decision in a precision farm. Fish appetite is a function of multiple interacting variables: water temperature, DO concentration, time since last feeding, fish size, social hierarchy, life stage, reproductive status, and health condition (24).

4.2 Underwater Computer Vision Systems

Convolutional neural networks (CNNs) trained on labelled video datasets have achieved uneaten pellet detection accuracies exceeding 92% in controlled trials (26), while behavioural classifiers trained to recognise feeding intensity from fish schooling dynamics have demonstrated correlation coefficients above 0.88 with manually labelled satiation scores (27). These systems feed signals to automated feed dispensers, implementing a closed-loop control system for appetite. Figure 2 illustrates the complete closed-loop AI feeding control flow.

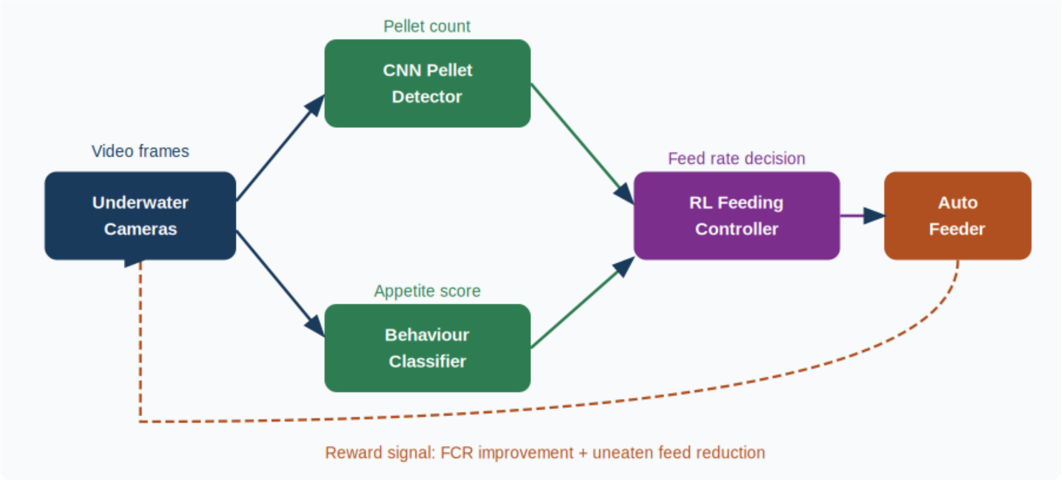

Figure 2: Closed-loop AI feeding control system integrating underwater CNN pellet detection, behavioural classification, and reinforcement learning (RL) controller with reward-based feedback

4.3 Feeding Technology Comparison

Table 2 summarises five generations of aquaculture feeding technology, from fixed-schedule feeders to RL-adaptive controllers, across control frequency, AI methodology, capital cost, and FCR deviation.

Table 2: Comparative overview of aquaculture feeding technologies ranked by automation sophistication, with estimated capital costs and feed conversion ratio (FCR) precision

Technology	Control Frequency	AI Method	Capital Cost (est.)	FCR Deviation
Fixed-schedule feeder	Basic (1–2×/day)	None	Low (< USD 1k/pen)	±20–30%
Demand feeder (pendulum)	Fish-triggered	Mechanosensory	Low (< USD 2k/pen)	±10–15%
Camera + threshold rule	Real-time appetite	Computer vision	Medium (USD 15–40k/pen)	±5–8%
CNN + pellet detector	Sub-minute	Deep learning	Medium-high (USD 40–80k)	±3–5%
RL adaptive controller	Continuous	RL + multi-sensor	High (> USD 80k/pen)	< ±2%

4.4 Biomass Estimation

Stereo-camera systems, which use two calibrated cameras to reconstruct three-dimensional body geometry, can now estimate mean individual weight to within 3–5% of the true value in real-time, without handling the fish (28). More recently, acoustic techniques — including split-beam echo-integration and acoustic Doppler current profilers — have been adapted for pen-based biomass assessment (29).

5. Genomic and Biotechnological Tools

5.1 Selective Breeding in the Digital Age

The application of genomic selection — which uses genome-wide single nucleotide polymorphism (SNP) genotyping arrays to estimate breeding values with high accuracy — has accelerated genetic gain rates in Atlantic salmon by two to three-fold relative to traditional pedigree-based selection (32). The cost of SNP genotyping has fallen to below USD 15 per individual in large-panel arrays, making population-scale genotyping economically feasible for commercial breeding programmes (33). Figure 3 shows the complete genomic selection cycle from broodstock population through to elite parent selection.

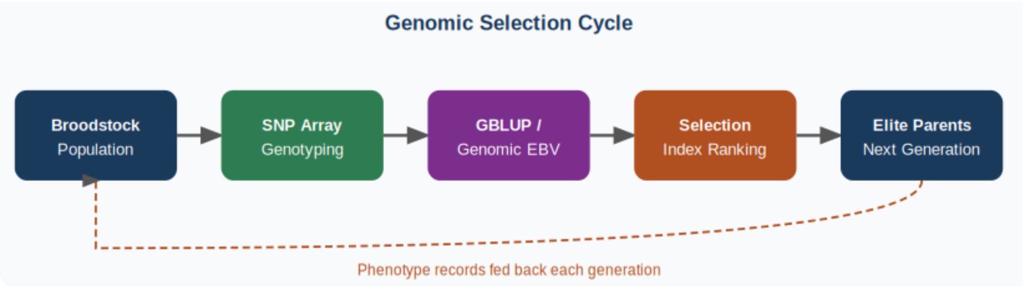

Figure 3: Genomic selection cycle in commercial aquaculture breeding: from SNP array genotyping through GBLUP-estimated breeding values (EBVs) to elite parent selection, with phenotype feedback across generations

5.2 Disease Resistance and Vaccination Support

Precision genomics is enabling the identification of QTLs conferring resistance to commercially important pathogens including ISAV, PDV, and sea lice. Incorporating genomic resistance markers into breeding indices can reduce ISAV-associated mortality by 35% within two to three generations of selection (34). Complementing genetic approaches, precision health monitoring systems — using metagenomic analysis of water and biofilm samples combined with machine learning classifiers — can detect pathogen signatures up to two weeks before clinical disease becomes apparent (35).

5.3 Environmental DNA

Within production systems, eDNA metabarcoding can characterise the full microbial community composition of pond or tank water from a single water sample, providing early warning of dysbiosis states associated with disease outbreaks (36). In the surrounding environment, eDNA surveys can quantify escapee salmon, monitor wild fish communities, and detect parasites at detection thresholds orders of magnitude below those achievable with traditional netting surveys (37).

6. Digital Twin Frameworks for Aquaculture

6.1 Concept and Architecture

A digital twin is a real-time, dynamic computational replica of a physical system, continuously updated by sensor data and capable of simulating system behaviour under hypothetical scenarios (38). In precision aquaculture, the concept is applied at three nested scales: the individual fish, the production unit, and the entire farm ecosystem (39). Figure 4 illustrates the bidirectional data flow between the physical farm and its digital twin, showing the sub-models that comprise the computational layer.

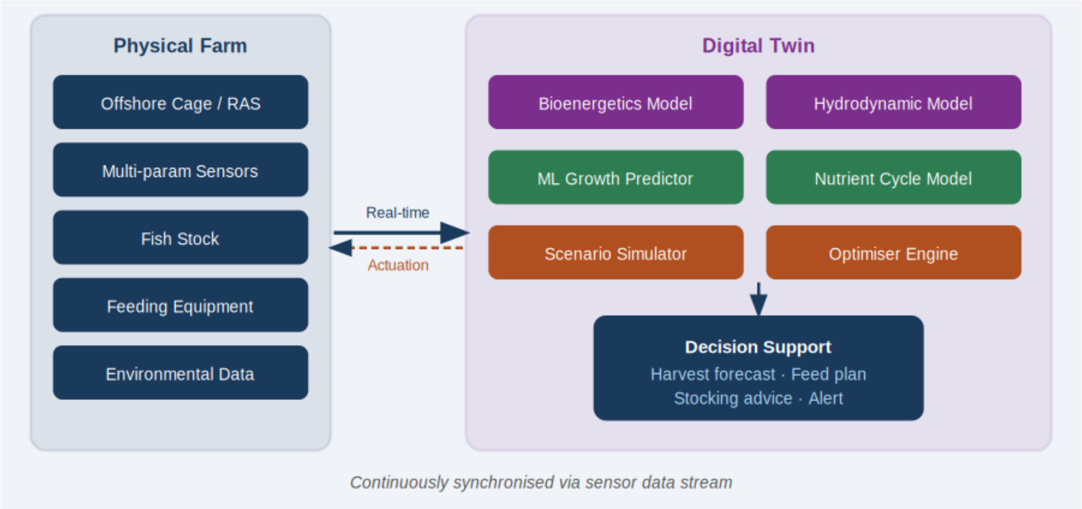

Figure 4. Digital twin architecture for precision aquaculture: physical farm (left) continuously synchronised with a multi-model computational twin (right) providing decision-support outputs

6.2 Industrial Implementations

Table 3 (Adoption Barriers) and Table 4 (Industrial Implementations) frame the current state of digital twin deployment. A fully realised aquaculture digital twin integrates mechanistic biological models — bioenergetics, biogeochemical, and hydrodynamic — with data-driven machine learning layers that account for process variability not captured by mechanistic equations (40).

Table 4: Selected commercial and pre-commercial digital twin implementations in aquaculture, by organisation, geographic scope, and deployment status

Organisation	**Country**	**Scope**	**Primary Output**	**Status**
SalmoSim	Norway / Scotland	Gut microbiome	In silico feed trial	In vitro validation; commercial stage
AquaCloud FarmTwin	Norway	Offshore cage	72-hr operational forecast	Active deployment; >30 farms
Hendrix Genetics	Netherlands	Breeding population	Genetic gain simulation	Internal R&D programme
AquaIntelligent	Canada	RAS tilapia	Full-cycle growth model	Pilot stage; 3 commercial RAS
BioSort AI	Scotland/Norway	Pen-level vision	Biomass & welfare twin	Commercial; multi-species

7. Barriers to Adoption

Despite rapid technological progress, significant technical, economic, structural, and infrastructure obstacles remain. Table 3 presents a consolidated matrix of adoption barriers, their severity ratings, identified mitigation pathways, and current status.

Table 3: Adoption barrier matrix for precision aquaculture systems: categories, severity ratings, mitigation strategies, and current state of resolution

Barrier	Category	Severity	Mitigation Pathway	Current Status
Sensor biofouling	Technical	High	Self-cleaning wipers, coatings	Ongoing R&D investment needed
Data interoperability	Technical	Medium	Open API standards	Fragmented market impedes progress
Capital cost	Economic	Very high	Financing, leasing models	Limits SME adoption globally
Workforce digital literacy	Structural	High	Vocational training reform	Curriculum lag behind technology
Rural connectivity	Infrastructure	Very high (developing)	LEO satellite (Starlink)	Narrowing but not yet closed
Model explainability	Technical/Trust	Medium	XAI integration	Critical for regulatory acceptance
Data governance	Regulatory	Medium–high	Sector-specific legislation	Ownership rights poorly defined

The capital cost of full precision aquaculture instrumentation can exceed USD 200,000 for a single offshore salmon pen, with ongoing maintenance costs of 15–20% of capital cost per year (47). For small- and medium-scale operators, who account for the majority of global aquaculture production, these costs are prohibitive without financing mechanisms or cooperative structures. Workforce readiness is a complementary challenge: precision aquaculture demands competencies in data literacy, remote monitoring system operation, and basic AI system oversight not yet embedded in most aquaculture vocational training curricula (48).

Figure 5 illustrates the commercial readiness level achieved across eight key technology domains, highlighting the maturity gap between established water quality IoT and emerging reinforcement learning controllers.

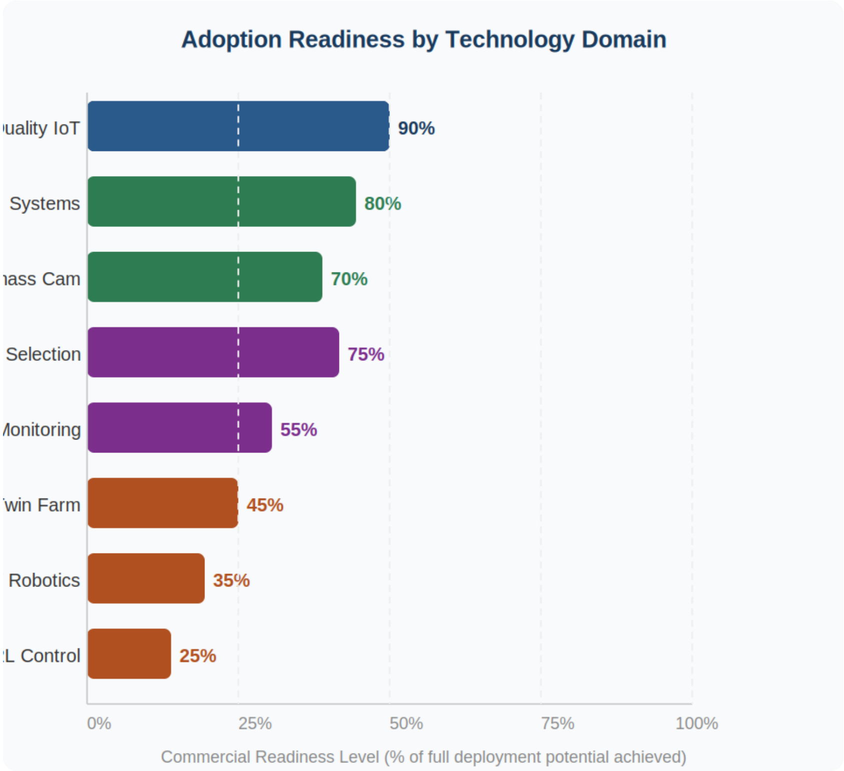

Figure 5: Commercial readiness levels across eight precision aquaculture technology domains, estimated as the percentage of full deployment potential currently achieved in commercial settings.

8. Regulatory and Ethical Dimensions

8.1 Data Governance

The data generated by precision aquaculture systems constitute a commercially and scientifically valuable resource. Ownership, access, and use rights for these data are not yet clearly defined in most jurisdictions. Farm operators may have limited awareness of the extent to which data collected on their behalf by technology providers are used for model training, competitive intelligence, or resale (50). This calls for clear contractual frameworks and potentially sector-specific data governance legislation.

8.2 Fish Welfare

Computer vision systems can detect welfare-relevant behaviours — including surface breathing, fin damage, cataract formation, and abnormal buoyancy — at a frequency and scale impossible for manual inspection (51). Several European regulatory frameworks now explicitly recognise automated welfare monitoring as a component of good aquaculture practice, and the EU's

Animal Welfare in Aquaculture Initiative (2023) references sensor-based monitoring as an enabling tool for welfare auditing (52).

8.3 Environmental Accountability

Precision aquaculture generates audit trails previously unavailable: continuous records of nutrient loading, antibiotic use, escapee events, and environmental conditions. Regulators in Norway, Scotland, and Canada are increasingly mandating electronic reporting of such data as a condition of operating licences (53).

9. Future Directions and Conclusions

Several technology trajectories are likely to reshape precision aquaculture over the coming decade. Soft robotics and autonomous underwater vehicles (AUVs) will increasingly be used for in-pen inspection, net cleaning, and targeted treatment delivery (54). Foundation models are beginning to be applied to aquaculture vision problems, offering the prospect of models that generalise across species and environments without requiring large species-specific training datasets (55). The convergence of precision aquaculture with advanced recirculating aquaculture systems (RAS) represents a particularly significant development: fully automated RAS facilities integrating AI-driven feeding, biofilter management, and welfare monitoring are already operational in Denmark, the Netherlands, and the United States (56).

Precision aquaculture is no longer a speculative technology domain. Sensor networks, computer vision, machine learning, genomic tools, and digital twin frameworks are being deployed at commercial scale across multiple species and production environments, delivering measurable improvements in resource efficiency, environmental performance, and fish welfare. The remaining challenges — cost, connectivity, explainability, data governance, and workforce capacity — are substantial but tractable. The transition from reactive to predictive to autonomous farm management is underway; its pace and equity of distribution will depend on the policy frameworks, financing instruments, and training ecosystems that governments and industry associations build around it.

References

1. Food and Agriculture Organization of the United Nations. (2022). *The state of world fisheries and aquaculture 2022*. FAO.
2. Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., Dempster, T., et al. (2018). Precision fish farming: A new framework to improve production in aquaculture. *Biosystems Engineering, 173*, 176–193.

3. Remen, M., Aas, T. S., Smedley, E., Torgersen, T., Mørkøre, T., Fjelldal, P. G., et al. (2021). Welfare and performance of Atlantic salmon maintained at different stocking densities. *Aquaculture, 545*, 737212.
4. Tseng, H. Y., & Chang, S. L. (2020). Emerging technologies in smart aquaculture. *Sensors, 20*(11), 3135.
5. Ervik, A., Thorsen, T., Aure, J., Stigebrandt, A., Johannessen, P., & Jahnsen, T. (2014). Regulating the local environmental impact of intensive marine fish farming. *Aquaculture, 158*, 85–94.
6. Verdegem, M. C. J., Bosma, R. H., & Verreth, J. A. J. (2006). Reducing water use for animal production through aquaculture. *International Journal of Water Resources Development, 22*(1), 101–113.
7. Brinker, A., & Kern-Staimer, C. (2019). A new generation of aquaculture facility management. *Aquacultural Engineering, 84*, 49–54.
8. Liu, Z., Li, Z., Wei, W., Zhu, H., & Ma, B. (2021). Intelligent aquaculture: AI applications in precision fish farming. *Computers and Electronics in Agriculture, 185*, 106128.
9. Boyd, C. E., & Tucker, C. S. (1998). *Pond aquaculture water quality management*. Kluwer Academic Publishers.
10. Boeuf, G., & Payan, P. (2001). How should salinity influence fish growth? *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 130*(4), 411–423.
11. Ievoli, C., Ambrosio, L., Punzo, E., & Cozzolino, M. (2021). The role of digital technologies in water quality monitoring for aquaculture. *Water, 13*(21), 3091.
12. Watanabe, E., Endo, H., & Takeuchi, N. (1999). Specific determination of creatinine by a film electrode based on creatinine amidohydrolase. *Biosensors and Bioelectronics, 14*(5), 495–501.
13. Mowlem, M. C., Floquet, N., Milani, A., Faber, M., Trivedi, I., Woodford, O., et al. (2021). Lab-on-chip sensors for water quality monitoring. *TrAC Trends in Analytical Chemistry, 109*, 116210.
14. Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems, 29*(7), 1645–1660.
15. Shi, X., Chen, Z., Wang, H., Yeung, D. Y., Wong, W. K., & Woo, W. C. (2015). Convolutional LSTM network: A machine learning approach for precipitation nowcasting. *Advances in Neural Information Processing Systems, 28*, 802–810.

16. Chen, Y., Song, L., Liu, Y., Yang, L., & Li, D. (2020). A review of the artificial neural network models for water quality prediction. *Applied Sciences, 10*(17), 5776.
17. Shi, J., Chen, J., Li, M., Zhang, Y., & Wei, M. (2021). Dissolved oxygen prediction using LSTM with spatiotemporal information in recirculating aquaculture systems. *Aquacultural Engineering, 95*, 102202.
18. Jobling, M. (1998). Fish bioenergetics. In D. H. Evans (Ed.), *The physiology of fishes* (pp. 311–340). CRC Press.
19. Cho, C. Y., & Bureau, D. P. (2001). A review of diet formulation strategies and feeding systems to reduce excretory and feed wastes in aquaculture. *Aquaculture Research, 32*(Suppl. 1), 349–360.
20. Ubina, N. A., & Cheng, S. C. (2022). A review of unmanned system technologies with its application to aquaculture farm monitoring and management. *Drones, 6*(1), 12.
21. Papadakis, V. M., Papadakis, I. E., Lamprianidou, F., Glaropoulos, A., & Kentouri, M. (2012). A computer-vision system and methodology for the analysis of fish behavior. *Aquacultural Engineering, 46*, 53–59.
22. Costa, C., Loy, A., Cataudella, S., Davis, D., & Scardi, M. (2006). Extracting fish size using stereo image analysis. *Aquacultural Engineering, 35*(3), 218–227.
23. Zhao, Z., Stelzenmüller, V., Zhu, Y., & Pesch, R. (2023). Acoustic methods for aquaculture biomass estimation: A review. *Reviews in Aquaculture, 15*(1), 113–130.
24. Meuwissen, T. H. E., Hayes, B. J., & Goddard, M. E. (2001). Prediction of total genetic value using genome-wide dense marker maps. *Genetics, 157*(4), 1819–1829.
25. Tsai, H. Y., Robledo, D., Lowe, N. R., Bekaert, M., Taggart, J. B., Bron, J. E., et al. (2016). Construction and annotation of a high-density SNP linkage map of the Atlantic halibut genome. *G3: Genes, Genomes, Genetics, 6*(10), 3257–3269.
26. Moen, T., Baranski, M., Sonesson, A. K., & Kjøglum, S. (2009). Confirmation and fine-mapping of a major QTL for resistance to infectious pancreatic necrosis in Atlantic salmon. *BMC Genomics, 10*, 368.
27. Tacchi, L., Bron, J. E., Taggart, J. B., Campbell, E. M., Bowman, A. S., Bricknell, I. R., et al. (2011). Multiple tissue transcriptomics of Atlantic cod during bacterial infection. *Diseases of Aquatic Organisms, 97*(3), 209–223.
28. Pawlowski, J., Kelly-Quinn, M., Altermatt, F., et al. (2018). The future of biotic indices in the ecogenomics era. *Science of the Total Environment, 637–638*, 1295–1310.
29. Hinlo, R., Gleeson, D., Lintermans, M., & Furlan, E. (2017). Methods to maximise recovery of environmental DNA from water samples. *PLoS ONE, 12*(6), e0179251.

30. Grieves, M. (2014). *Digital twin: Manufacturing excellence through virtual factory replication* (White Paper).
31. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics, 15*(4), 2405–2415.
32. Fore, M., Frank, K., Dempster, T., Alfredsen, J. A., & Svendsen, E. (2020). Precision fish farming: A new framework for the future of aquaculture. *PLoS ONE, 15*, e0230573.
33. Moe, H., Gaarder, R. H., Olsen, A., & Hopperstad, O. S. (2010). Loads from current and waves on aquaculture net cages. *Journal of Fluids and Structures, 26*(3), 469–479.
34. Dempster, T., Gunnarsson, H., Glover, K. A., & Skilbrei, O. T. (2021). Farmed Atlantic salmon in the wild: A review of ranges, incidence and consequences. *Reviews in Aquaculture, 13*(3), 1344–1377.
35. Bronson, K. (2019). Looking through a responsible innovation lens at uneven engagements with digital farming. *NJAS: Wageningen Journal of Life Sciences, 90–91*, 100294.
36. Noble, C., Gismervik, K., Iversen, M. H., Kolarevic, J., Nilsson, J., Stien, L. H., & Turnbull, J. F. (Eds.). (2018). *Welfare indicators for farmed Atlantic salmon*. Nofima.
37. European Commission. (2023). *Animal welfare in aquaculture initiative*. European Commission.
38. Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., et al. (2015). Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. *ICES Journal of Marine Science, 72*(3), 997–1021.
39. Roper, D. T., Sharma, S., Sutton, R., & Culverhouse, P. (2011). A review of developments towards autonomy in surface vessels for the maritime sector. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 225*(3), 151–173.
40. Bommasani, R., Hudson, D. A., Aditi, A., Altman, R., Arora, S., et al. (2021). *On the opportunities and risks of foundation models*. arXiv. https://arxiv.org/abs/2108.07258
41. Dalsgaard, J., Lund, I., Thorarinsdottir, R., Drengstig, A., Arvonen, K., & Pedersen, P. B. (2013). Farming different species in RAS in Nordic countries. *Aquacultural Engineering, 53*, 2–9.

LIVESTOCK WASTE MANAGEMENT FOR ENVIRONMENTAL SUSTAINABILITY

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Abstract

Livestock production generates large quantities of manure and associated wastes that, if improperly managed, can lead to water and soil pollution, greenhouse gas emissions, and public health risks. However, livestock waste is a valuable source of organic matter and nutrients that can be transformed into useful products through sustainable management practices. This chapter discusses the types and characteristics of livestock waste, its environmental impacts, and major waste management technologies, including composting, anaerobic digestion, vermicomposting, solid–liquid separation, wastewater treatment, and biochar production. It also highlights circular economy approaches that promote nutrient recycling, renewable energy generation, and resource recovery. Adoption of these integrated strategies can minimize environmental pollution, enhance resource use efficiency, and support sustainable and resilient livestock production systems.

Keywords: Livestock Waste, Waste Management, Vermicomposting, Biochar.

Introduction

Livestock production is a vital component of global agriculture, contributing significantly to food security, nutritional well-being, rural livelihoods, and economic development. The sector supplies essential animal-derived products, including milk, meat, eggs, fiber, and draft power, while supporting the livelihoods of more than one billion people worldwide, particularly in developing countries. According to the Food and Agriculture Organization (FAO), livestock contributes approximately 40% of the global agricultural gross domestic product (GDP) and plays a pivotal role in sustaining agricultural economies through employment generation, income diversification, and nutrient cycling within integrated farming systems (FAO, 2023). In India, livestock is recognized as one of the fastest-growing subsectors of agriculture, accounting for nearly one-third of the agricultural GDP and serving as a crucial source of income for millions of smallholders and marginal farmers.

Although intensified livestock production systems have enhanced productivity and profitability, they have simultaneously generated enormous quantities of animal waste, creating significant environmental and public health challenges (Parihar *et al.,* 2019). Livestock waste primarily comprises animal manure, urine, bedding materials, spilled feed, wastewater, carcasses, and residues from animal housing and processing facilities. If inadequately managed, these wastes become major sources of environmental pollution through the release of nutrients, pathogens, organic matter, greenhouse gases, antibiotics, heavy metals, and other contaminants. Traditionally viewed as a disposal problem, animal waste is now considered an important component of circular bio-economy frameworks due to its potential for nutrient recycling, renewable energy generation, and soil health improvement. Animal manure contains substantial amounts of essential plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), and various micronutrients, making it an excellent organic fertilizer capable of improving soil fertility, enhancing microbial activity, and increasing soil organic carbon. When appropriately processed and managed, livestock waste contributes to sustainable agricultural production by reducing dependence on synthetic fertilizers and improving soil physical, chemical, and biological properties.

Despite these benefits, inefficient waste management practices remain widespread in many regions, particularly in developing countries. Improper storage, uncontrolled discharge, open dumping, and indiscriminate land application of livestock waste contribute significantly to soil degradation, eutrophication of surface water bodies, groundwater contamination, offensive odors, vector proliferation, and the emission of greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) (IPCC,2022). These emissions account for a considerable proportion of agriculture's contribution to global climate change.

Governments, international organizations, and environmental agencies have introduced various policies and regulatory frameworks aimed at improving livestock waste management practices. International initiatives such as the Sustainable Development Goals (SDGs), the Paris Agreement, and the Global Methane Pledge emphasize the importance of reducing agricultural pollution and greenhouse gas emissions through sustainable manure management. This chapter provides a comprehensive overview of livestock waste management for environmental sustainability.

Characteristics of Livestock Waste

Livestock waste is an inevitable by-product of animal production systems and represents one of the largest sources of organic residues generated by the agricultural sector. Livestock waste encompasses all solid, liquid, and semi-solid materials produced during animal rearing, housing, feeding, processing, and slaughtering activities. Livestock waste can be broadly classified into solid waste, liquid waste, gaseous emissions, and biological waste based on its physical state and origin. Solid waste primarily consists of animal feces, manure mixed with bedding materials (such as straw, sawdust, rice husk, and wood shavings), spilled feed, leftover fodder, hair, feathers, and litter generated from poultry houses. It also includes carcasses, placental tissues, and slaughterhouse by-products. These materials are rich in organic carbon and nutrients, making them suitable for composting, vermicomposting, and bioenergy production. Liquid waste comprises urine, wash water from animal sheds, milking parlors, cooling systems, and wastewater generated during cleaning operations. Liquid manure contains dissolved nitrogen, phosphorus, potassium, salts, suspended solids, and pathogenic microorganisms, requiring appropriate treatment before disposal or agricultural reuse. Gaseous wastes are generated during manure storage, decomposition, and land application, including methane (CH_4), ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2), and hydrogen sulfide (H_2S). These gases contribute to climate change, acidification, odor problems, and reduced air quality. Biological wastes include pathogenic bacteria, viruses, fungi, parasites, antibiotic residues, and antimicrobial resistance genes that may pose risks to human, animal, and environmental health if not adequately treated.

The quantity and characteristics of livestock waste vary considerably depending on animal species, body weight, feed composition, housing systems, water consumption, production stage, climatic conditions, and management practices. Dairy cattle and buffaloes generally produce the largest quantities of manure because of their large body size and high feed intake, whereas poultry generate comparatively smaller quantities per bird but produce highly concentrated waste rich in nitrogen and phosphorus. Pig manure is characterized by high moisture content and considerable concentrations of organic matter, while sheep and goat manure is relatively dry and nutrient dense. Consequently, waste management strategies should be designed according to species-specific waste characteristics to maximize nutrient recovery and minimize environmental impacts.

Environmental Impacts of Improper Livestock Waste Management

Although livestock waste is a valuable source of organic matter and essential plant nutrients, its improper handling, storage, treatment, and disposal can have profound consequences for environmental quality and public health (Martinez *et al.,* 2009). Uncontrolled release of livestock waste introduces excessive nutrients, organic pollutants, pathogens, pharmaceuticals, and greenhouse gases into the environment, disrupting ecosystem functions and threatening the sustainability of agricultural production systems. The magnitude of these impacts depends on livestock density, manure management practices, climatic conditions, soil characteristics, and the capacity of surrounding ecosystems to assimilate waste. Consequently, environmentally scientific waste management has become a critical component of sustainable livestock production and climate-resilient agriculture.

Water Pollution

Water pollution is one of the most significant environmental consequences of improper livestock waste management. Animal manure contains high concentrations of nitrogen, phosphorus, organic carbon, suspended solids, salts, and diverse microorganisms. When manure is applied to agricultural land in quantities exceeding crop nutrient requirements or is stored without adequate containment, rainfall and irrigation can transport nutrients and contaminants into nearby rivers, lakes, reservoirs, and groundwater aquifers. Nitrogen is particularly susceptible to leaching in the form of nitrate, while phosphorus is commonly transported through surface runoff attached to soil particles. Elevated nitrate concentrations in groundwater can impair drinking water quality and pose health risks, whereas excessive phosphorus inputs stimulate eutrophication, resulting in harmful algal blooms, oxygen depletion, fish mortality, and loss of aquatic biodiversity. Livestock wastewater also exhibits a high biochemical oxygen demand (BOD) and chemical oxygen demand (COD), reflecting its elevated organic matter content. When untreated effluents enter surface water bodies, microbial decomposition consumes dissolved oxygen, creating hypoxic conditions that adversely affect aquatic organisms.

Air Pollution and Greenhouse Gas Emissions

Improper storage and handling of livestock waste contribute substantially to atmospheric pollution through the emission of gases and particulate matter. During microbial decomposition of manure under anaerobic conditions, methane (CH_4) is produced, whereas nitrous oxide (N_2O) is generated through nitrification and denitrification processes in soils and manure storage systems. Carbon dioxide (CO_2) is released during aerobic decomposition of organic matter. Methane and nitrous oxide possess significantly greater global warming potential than carbon dioxide and therefore make an important contribution to climate change. Livestock manure is also a major source of ammonia (NH_3), which volatilizes during storage, handling, and field application. Ammonia emissions reduce fertilizer nitrogen use efficiency and contribute to atmospheric particulate matter formation, acidification of terrestrial ecosystems, and nutrient imbalances. Furthermore, gases such as hydrogen sulfide (H_2S) and volatile organic compounds (VOCs) generated from decomposing manure are responsible for unpleasant odors and can adversely affect air quality around livestock production facilities.

Soil Degradation

Improper management of livestock waste is a major cause of soil degradation, particularly in regions with intensive animal production systems. When manure, slurry, or other livestock wastes are applied excessively, stored improperly, or disposed of without appropriate treatment, they alter the physical, chemical, and biological properties of soil. Although livestock waste contains valuable nutrients and organic matter that can improve soil fertility when applied judiciously, uncontrolled disposal leads to nutrient imbalance, contamination, and deterioration of soil quality. In addition to nutrient-related problems, livestock waste may introduce trace metals such as copper and zinc, which are commonly present in feed supplements. Long-term accumulation of these elements can alter soil microbial communities and impair soil biological functions. Traditional livestock manure management practices, particularly the direct application of untreated manure to agricultural fields, can contribute to soil degradation, nutrient enrichment of aquatic ecosystems (eutrophication), and increased emissions of environmentally harmful gases (Tryhuba *et al.,* 2025). Residues of veterinary pharmaceuticals and antibiotics may further influence microbial diversity and nutrient cycling processes. Leaching of nitrogenous compounds and total organic carbon (TOC) from livestock waste further accelerates soil degradation (Yeum *et al.,* 2025). Rainfall-driven infiltration transports dissolved nitrate, ammonium, and organic carbon into deeper soil horizons, reducing nutrient availability in the root zone and degrading groundwater quality. The movement of TOC also alters soil carbon dynamics, affecting microbial processes and potentially mobilizing heavy metals and other contaminants present in the soil.

Public Health Concerns

Improper livestock waste management presents several direct and indirect risks to public health. Animal manure can contain pathogenic bacteria, viruses, protozoa, and parasitic organisms capable of contaminating food, water, and the surrounding environment. If manure is inadequately treated before land application or enters drinking water sources, disease transmission may occur through contaminated water, fresh produce, or direct human contact. Poor waste management also creates favorable breeding conditions for insects and rodents, increasing the potential for disease vectors in farming communities.

Livestock Waste Management Technologies

The adoption of efficient waste management technologies has become an essential component of sustainable livestock production. Modern livestock waste management aims not only to minimize environmental impacts but also to recover valuable resources such as nutrients, renewable energy, and organic soil amendments. The selection of an appropriate waste management technology depends on several factors, including animal species, housing system, manure consistency, climatic conditions, farm size, economic feasibility, and intended end use of the recovered products. Some technologies for waste management are discussed below:

Collection and Storage

Efficient collection and storage constitute the first and most critical steps in livestock waste management. Proper collection minimizes nutrient losses, reduces odor generation, prevents pathogen dissemination, and facilitates subsequent treatment and utilization processes. Livestock manure may be collected manually or mechanically depending on the production system. In dairy and beef farms, manure is commonly removed using mechanical scrapers, conveyor belts, vacuum systems, or flushing systems, whereas poultry litter is generally collected after each production cycle. Pig production systems often employ slatted floors that allow manure to accumulate beneath animal housing before periodic removal.

After collection, manure must be stored under conditions that preserve its nutrient value while minimizing environmental contamination. Solid manure is usually stored on impermeable concrete platforms with adequate drainage systems to prevent leachate infiltration into surrounding soil and groundwater. Liquid manure is commonly stored in lagoons, concrete tanks, or covered storage facilities.

Composting

Composting is one of the most widely adopted biological methods for stabilizing livestock waste. It is an aerobic microbial process in which bacteria, fungi, and actinomycetes decompose biodegradable organic matter into a stable, humus-like product under controlled environmental conditions. During composting, microorganisms utilize organic carbon as an energy source while converting complex organic compounds into simpler, stable substances. The process typically progresses through mesophilic, thermophilic, cooling, and maturation phases. The thermophilic phase is particularly important because temperatures between 55 and 65°C destroy most pathogenic microorganisms, weed seeds, and parasite eggs, thereby improving the sanitary quality of the final compost. Efficient composting requires an appropriate carbon-to-nitrogen (C:N) ratio, generally between 25:1 and 30:1, moisture content of approximately 50–60%, adequate oxygen supply, and regular turning to maintain aerobic conditions. The resulting compost is rich in stabilized organic matter and plant nutrients and can be applied as an organic fertilizer to improve soil fertility, soil structure, water-holding capacity, and microbial activity.

Anaerobic Digestion and Biogas Production

Anaerobic digestion is a biological process in which microorganisms decompose organic matter in the absence of oxygen to produce biogas and nutrient-rich digestate. It has become one of the most effective technologies for simultaneously managing livestock waste, generating renewable energy, and reducing greenhouse gas emissions. The digestion process involves four sequential stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During these stages, complex organic compounds are converted into simpler molecules that methanogenic microorganisms transform into methane and carbon dioxide. Biogas produced through anaerobic digestion generally contains 50–70% methane, 30–45% carbon dioxide, and small quantities of hydrogen sulfide, water vapor, and trace gases. The methane-rich gas can be utilized for cooking, heating, electricity generation, and combined heat and power systems, thereby reducing dependence on fossil fuels. After digestion, the remaining digestate retains a significant proportion of the original nutrients, including nitrogen, phosphorus, and potassium (Chowdhury *et al.,* 2020).

Vermicomposting

Vermicomposting is an environmentally friendly biotechnology that utilizes earthworms and associated microorganisms to convert livestock manure into a highly stabilized organic fertilizer known as vermicompost. Earthworm species such as *Eisenia fetida*, *Eudrilus eugeniae*, and *Perionyx excavatus* are commonly used because of their high feeding rates and rapid reproduction. During vermicomposting, earthworms ingest partially decomposed organic matter and fragment it into smaller particles, increasing the surface area available for microbial decomposition. Simultaneously, microorganisms further mineralize organic compounds, producing nutrient-rich casts that contain readily available nitrogen, phosphorus, potassium, micronutrients, humic substances, and beneficial microorganisms. Compared with conventional compost, vermicompost generally contains higher concentrations of plant-available nutrients, greater microbial diversity, and enhanced concentrations of plant growth-promoting compounds

Wastewater Treatment

Livestock farms generate considerable quantities of wastewater through animal washing, floor cleaning, milking operations, feed preparation, and equipment sanitation. This wastewater typically contains suspended solids, organic matter, nutrients, detergents, pathogens, and veterinary pharmaceuticals. Effective wastewater treatment usually involves a combination of physical, chemical, and biological processes. Preliminary treatment removes coarse solids through screening and sedimentation. Biological treatment methods, including activated sludge systems, oxidation ponds, anaerobic lagoons, sequencing batch reactors, and constructed wetlands, facilitate microbial degradation of organic pollutants and nutrient removal. Advanced treatment technologies such as membrane filtration, ultraviolet disinfection, and advanced oxidation processes further improve effluent quality where water reuse is intended. Properly treated wastewater can be safely reused for irrigation, cleaning operations, or groundwater recharge, thereby conserving freshwater resources.

Biochar Production

Biochar production has emerged as an innovative strategy for converting livestock waste into a stable carbon-rich material with multiple agricultural and environmental benefits. Biochar is produced through pyrolysis, a thermochemical process in which organic biomass is heated under limited or no oxygen conditions at temperatures generally ranging from 300 to 700°C. During pyrolysis, volatile compounds are released while stable carbon structures are formed. Depending on operating conditions, the process also generates bio-oil and combustible gases that can be recovered as renewable energy sources. Livestock manure-derived biochar possesses a porous structure, large surface area, high cation exchange capacity, and appreciable concentrations of phosphorus, potassium, calcium, and magnesium. Application of biochar improves soil physical, chemical, and biological properties by increasing water retention, enhancing nutrient availability, promoting beneficial microbial activity, and reducing nutrient leaching.

Circular Economy Approaches in Livestock Waste Management

The circular economy provides a sustainable framework for livestock waste management by transforming animal waste from an environmental burden into a valuable resource that is continuously recovered, recycled, and reintegrated into agricultural production systems. Unlike the conventional linear model of "produce–use–dispose," the circular economy emphasizes resource efficiency, waste minimization, and closed-loop nutrient cycling. Livestock manure, urine, bedding materials, and processing residues are rich in organic matter and essential nutrients, including nitrogen, phosphorus, potassium, and micronutrients, which can be recovered through technologies such as composting, anaerobic digestion, vermicomposting, biochar production, nutrient recovery systems, and wastewater recycling. These approaches convert livestock waste into marketable products such as organic fertilizers, biofertilizers, soil conditioners, biogas, biomethane, electricity, and heat, thereby reducing dependence on synthetic fertilizers and fossil fuels while lowering greenhouse gas emissions and environmental pollution. Integration of crop–livestock systems further enhance circularity by returning stabilized manure and digestate to agricultural fields, improving soil fertility, increasing soil organic carbon, enhancing microbial activity, and promoting long-term soil health. Recent advances in precision livestock farming, digital monitoring, artificial intelligence, and Internet of Things (IoT)-based nutrient management have strengthened circular economy practices by enabling accurate estimation of manure production, nutrient composition, storage conditions, and field application rates, thereby improving nutrient use efficiency and minimizing losses through leaching, runoff, and gaseous emissions. Moreover, resource recovery from livestock waste contributes to renewable energy generation, climate change mitigation, water conservation, and rural economic development by creating additional income opportunities for farmers and reducing waste management costs. Adoption of circular economy principles is therefore increasingly recognized as a key strategy for achieving sustainable livestock production, supporting climate-smart agriculture, conserving natural resources, and advancing global sustainable development goals through efficient utilization of biological resources and reduction of environmental footprints.

Conclusion

Modern livestock waste management technologies transform manure from an environmental liability into a valuable resource. Collection and proper storage preserve nutrient value and minimize pollution, while composting, anaerobic digestion, vermicomposting, solid–liquid separation, wastewater treatment, and biochar production facilitate nutrient recycling, renewable energy generation, soil improvement, and environmental protection. Integrating these technologies according to local conditions, livestock production systems, and resource availability enhances waste utilization efficiency and supports sustainable livestock production. Continued technological innovation, policy support, and farmer awareness will further strengthen the role of livestock waste management in achieving climate resilience, resource conservation, and circular agricultural systems.

References

1. Chowdhury, T., Chowdhury, H., Hossain, N., Ahmed, A., Hossen, M. S., Chowdhury, P., Thirugnanasambandam, M., & Saidur, R. (2020). Latest advancements on livestock waste management and biogas production: Bangladesh's perspective. *Journal of Cleaner Production, 272*, 122818.
2. Food and Agriculture Organization of the United Nations. (2023). *The State of Food and Agriculture*. Food and Agriculture Organization of the United Nations.
3. Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Mitigation of climate change*. Intergovernmental Panel on Climate Change.
4. Martinez, J., Dabert, P., Barrington, S., & Burton, C. (2009). Livestock waste treatment systems for environmental quality, food safety, and sustainability. *Bioresource Technology, 100*(22), 5527–5536.
5. Parihar, S. S., Saini, K. P. S., Lakhani, G. P., Jain, A., Roy, B., Ghosh, S., & Aharwal, B. (2019). Livestock waste management: A review. *Journal of Entomology and Zoology Studies, 7*(3), 384–393.
6. Tryhuba, A., Mudryk, K., Tryhuba, I., Kotsylovskyi, M., Sorokin, D., Bezaltychna, O., Pysz, P., & Hutsol, T. (2025). Models for sustainable management of livestock waste based on neural network architectures. *Scientific Reports, 15*(1), 28082.

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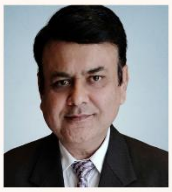

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