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SURROGACY TECHNOLOGY IN AQUACULTURE: A NEW FRONTIER FOR SUSTAINABLE FISH PRODUCTION

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Abstract

Surrogate broodstock technology is an emerging reproductive biotechnology in aquaculture that enables the production of donor-derived gametes through germ cell transplantation into sterile recipient fish. The technology supports endangered-species conservation, rapid multiplication of elite germplasm, and genetic improvement of commercially important fish. Successful applications in salmonids, tuna, sturgeons, tilapia, and Indian major carps demonstrate its growing importance in sustainable aquaculture. This article discusses the principles, applications, case studies, and prospects of surrogacy technology in global and Indian aquaculture systems.

Introduction

Aquaculture presently contributes substantially to global seafood production and is increasingly recognized as a solution to future food security challenges. Global estimates suggest demand for aquatic protein will continue to rise with population growth and changing dietary patterns. Scientific innovations and genetic technologies are therefore becoming essential tools for improving aquaculture productivity and sustainability (Costello et al., 2020).

Unlike terrestrial livestock species that have undergone centuries of domestication and selective breeding, most cultured aquatic organisms remain genetically close to their wild ancestors (Teletchea and Fontaine, 2014). Consequently, aquaculture faces several persistent challenges, including low reproductive efficiency, poor seed availability, overexploitation of broodstock, disease outbreaks, and declining wild fish populations. In many economically important fishes, maturation occurs late, and broodstock maintenance becomes expensive and risky.

To address these issues, surrogate broodstock technology has emerged as an advanced reproductive biotechnology. The technology enables the production of gametes from one species within another compatible host species. This innovative approach not only facilitates rapid multiplication of elite germplasm but also offers opportunities for the conservation of endangered fishes and the enhancement of breeding programmes.

Concept of Surrogate Broodstock Technology

Surrogate broodstock technology involves producing donor-derived sperm or eggs within a recipient fish. In this process, germ cells from a donor fish are transplanted into sterile recipient fish (Fig. 1), where they colonize the gonads and eventually produce functional gametes of donor origin (Yoshizaki and Yazawa, 2019). The term “surrogate” indicates replacement, while “broodstock” refers to mature breeding fish used for seed production. The technology primarily utilises two categories of germ cells:

a) Primordial Germ Cells (PGCs) b) Gonial Cells

These cells possess the capacity to develop into functional sperm or eggs after successful transplantation.

1. The major components of surrogate technology include:
2. Selection of donor and recipient species
3. Isolation of germ cells
4. Sterilisation of recipient hosts
5. Germ cell transplantation
6. Colonisation and gamete production

This technology has become particularly important for species with long generation intervals, large body size, endangered populations, or difficulties in captive breeding.



Mechanism of Surrogacy Technology

Isolation of Germ Cells

The first step involves the extraction of germline stem cells from donor fish. Germ cells may be isolated either from embryos (PGCs) or mature gonads (gonial cells).

Primordial Germ Cells (PGCs)

PGCs are early embryonic cells destined to become gametes. In teleost fishes, these cells originate from maternal germplasm and migrate during embryonic development towards the gonadal region (Extavour and Akam, 2003). Researchers commonly label PGCs using fluorescent proteins linked with germline-specific genes such as vasa for easier identification and isolation (Kobayashi et al., 2007).

One limitation of PGC utilisation is its extremely low abundance. Studies in zebrafish and medaka have shown that each embryo contains only a small number of PGCs (Saito et al., 2006).

Gonial Cells

Gonial cells such as spermatogonia and oogonia are obtained from mature testes or ovaries. Compared to PGCs, gonial cells are available in much larger quantities and are easier to culture and cryopreserve (Lee et al., 2013). Isolation is generally performed through enzymatic dissociation and filtration of gonadal tissues.

Sterilisation of the Recipient Fish

For successful donor-derived gamete production, recipient fish must be sterilised so that their own germ cells do not compete with transplanted cells. Common sterilisation methods include:

1. Triploidization
2. Hybridization

Gene knockdown or CRISPR/Cas9-mediated knockout of germ-cell-related genes such as *dead end* (*dnd1*) has been effectively used to produce sterile recipients in fish, including zebrafish, salmon, trout, and tilapia (Wargelius et al., 2016).

Germ Cell Transplantation

Transplantation can be performed at different developmental stages:

- a) Blastula-stage embryos
- b) Hatchlings or larvae
- c) Adult fishes

Usually, donor germ cells are injected into the peritoneal cavity of recipient larvae, where they migrate naturally towards developing gonads. Because the immune system of larvae is still immature, chances of rejection are reduced (Okutsu et al., 2006). After colonisation, donor cells proliferate and produce functional sperm or eggs according to the sex of the recipient fish.

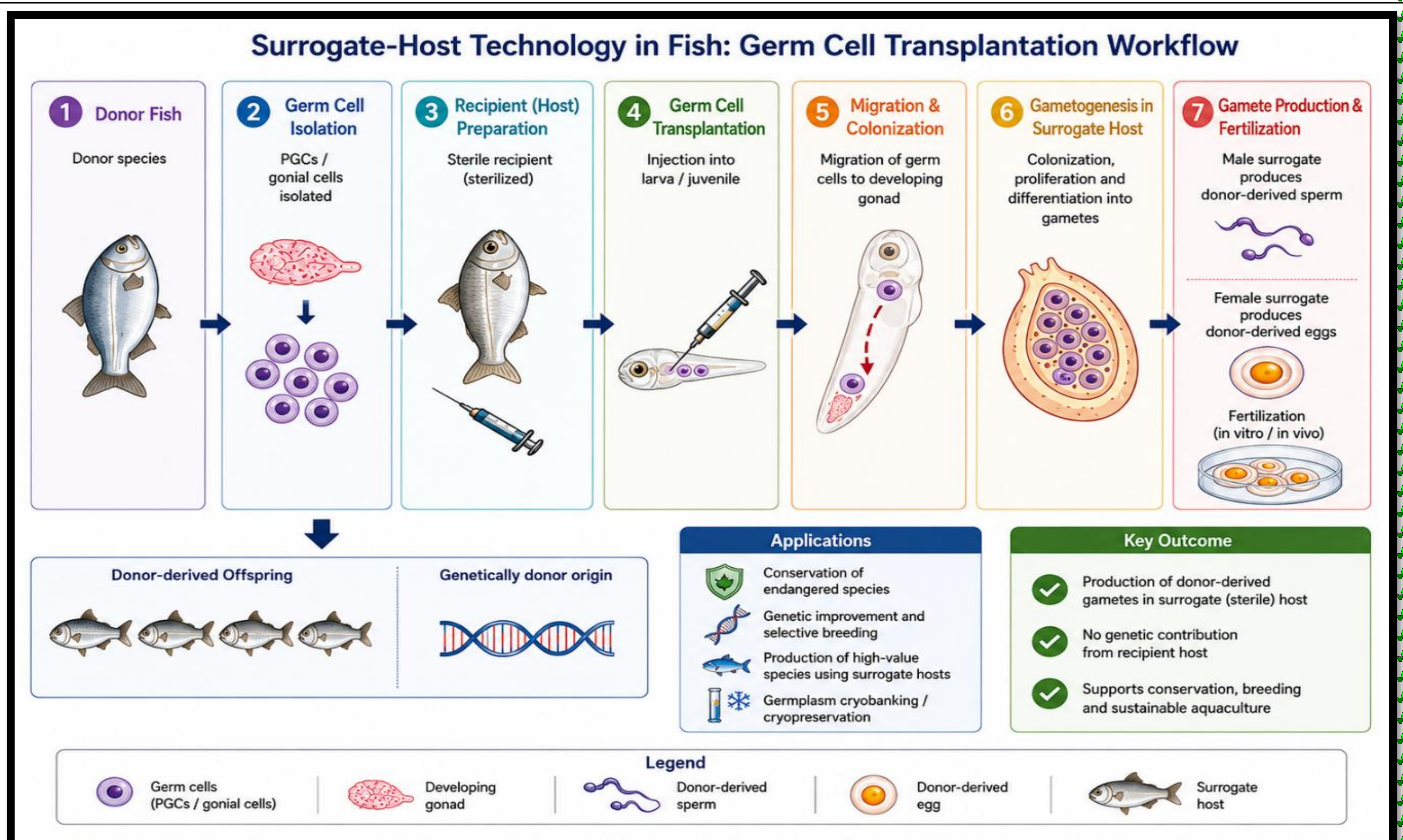


Fig. 1: Schematic representation of surrogate broodstock technology in aquaculture.

Global Case Studies of Surrogacy Technology

1. Salmonids in Japan

The pioneering work in surrogate broodstock technology was conducted in Japan by researchers led by Goro Yoshizaki. In a landmark experiment, rainbow trout germ cells were transplanted into masu salmon recipients. The surrogate salmon successfully produced rainbow trout sperm and eggs, resulting in viable offspring (Takeuchi et al., 2004).

This study demonstrated for the first time that one fish species could produce functional gametes of another species. The success revolutionised fish reproductive biotechnology and established the foundation for modern surrogate technology.

Significance:

- Reduced broodstock maintenance costs
- Preservation of elite germplasm
- Faster breeding cycles

2. Pacific Bluefin Tuna Surrogacy in Japan

The Pacific bluefin tuna is one of the most valuable marine fish globally, but maintaining broodstock is extremely difficult due to its enormous size. Japanese scientists successfully transplanted tuna germ cells into smaller mackerel-related surrogate fish.

This approach offered the possibility of producing tuna gametes from small laboratory-manageable fish, thereby reducing infrastructure and operational costs significantly.

Significance:

- Conservation of endangered tuna populations
- Easier hatchery management
- Potential commercial seed production

3. Sturgeon Conservation in Europe

Several sturgeon species face severe population decline because of overfishing and habitat degradation. European researchers developed germ cell transplantation methods using sterlet as a recipient species for endangered sturgeons. Successful donor-derived gamete production has opened new possibilities for conservation hatcheries and restoration programmes.

Significance:

- Conservation of critically endangered fishes
- Long-term germplasm preservation
- Reduction in exploitation of wild broodstock

4. Zebrafish Germline Chimeras

In the United States and Japan, zebrafish became an important model species for studying germline transplantation. Wong et al. (2011) successfully transplanted ovarian germ cells into sterile zebrafish larvae and produced donor-derived offspring.

Importance:

- Understanding germ cell biology
- Development of stem cell technologies
- Model for future aquaculture applications

5. Nile Tilapia in China

Chinese researchers integrated CRISPR/Cas9 genome editing with surrogate technology to produce sterile tilapia recipients. Donor germ cells were transplanted successfully, leading to donor-derived gamete formation.

Importance:

- Genetic containment

- Improved breeding programmes
- Development of monosex culture systems

Indian Scenario and Case Studies

India possesses enormous aquaculture diversity and significant potential for applying surrogate broodstock technology, especially in Indian major carps, catfishes, mahseer, and endangered indigenous fishes.

1. Indian Major Carps

Researchers in India have initiated studies on germ cell transplantation in Indian major carps, such as *Catla catla*, *Labeo rohita*, and *Cirrhinus mrigala*. The aim is to develop smaller surrogate species capable of producing gametes of commercially important carps.

Potential Benefits

- Rapid multiplication of elite broodstock
- Preservation of threatened carp germplasm
- Improved hatchery productivity

2. Conservation of Mahseer

The iconic mahseer fish of India are declining due to habitat destruction and river fragmentation. Surrogate technology offers a promising approach for conserving mahseer germplasm through cryopreservation and transplantation into compatible hosts.

Institutions such as the ICAR-Central Institute of Fisheries Education and ICAR-Central Institute of Freshwater Aquaculture are actively exploring advanced reproductive biotechnologies for indigenous fish conservation.

3. Cryopreservation Research in India

Indian laboratories have increasingly focused on cryobanking of fish germ cells and the development of transplantation protocols. Such efforts are essential for future surrogate breeding programmes and long-term aquatic biodiversity conservation.

Advantages of Surrogacy Technology

1. Conservation of Endangered Species: The technology enables the preservation and propagation of threatened species without continuous dependence on wild broodstock.
2. Reduction in Broodstock Size: Large fishes such as tuna can be propagated using smaller surrogate species, greatly reducing infrastructure costs.
3. Rapid Genetic Improvement: Elite germplasm can be multiplied rapidly, accelerating selective breeding programmes.
4. Cryopreservation and Gene Banking: Frozen germ cells can later be revived through surrogate hosts, ensuring long-term genetic conservation.

5. Disease-Free Seed Production: Healthy donor-derived gametes may support the production of disease-free fish seed.

Table 1 Selected case studies on surrogate broodstock technology and germ-cell transplantation in fish.

Year	Surrogate system / approach	Donor species / donor cell	Recipient / surrogate host	Aim / major outcome	Reference
2025	Cryopreserved germ-cell transplantation for endangered fish conservation	Tokyo bitterling, <i>Tanakia tanago</i> ; cryopreserved testicular germ cells	Oily bitterling, <i>Tanakia limbata</i> ; sterile/dnd-knockdown recipients	Produced functional donor-derived eggs and sperm; offspring showed Tokyo bitterling genotype and morphology; proposed for ex situ conservation of endangered species.	Yamakawa et al., 2025
2025	Surrogate males for invasive fish reproductive control	Brown trout, <i>Salmo trutta</i> ; type A spermatogonia / germline stem cells	Triploid rainbow trout, <i>Oncorhynchus mykiss</i>	Created rainbow trout males producing brown trout sperm; natural mating with rainbow trout females generated lethal hybrids, proposed as a biological control tool for invasive trout.	Amano et al., 2025
2024	Small-bodied tuna surrogate for bluefin tuna sperm production	Pacific bluefin tuna, <i>Thunnus orientalis</i> ; testicular germ cells	Hybrid little tuna, <i>Euthynnus affinis</i> × <i>E. alletteratus</i>	Produced functional donor-derived Pacific bluefin tuna sperm at about 8 months and	Kawamura et al., 2024



				~1 kg body size, reducing space, time and cost for bluefin tuna breeding.	
2024	Repeated gamete production of semelparous salmon in iteroparous host	Chinook salmon and kokanee salmon germline stem cells	Rainbow trout, <i>Oncorhynchus mykiss</i>	Demonstrated that salmon germline stem cells can survive in rainbow trout and repeatedly supply donor-derived salmon gametes for multiple years.	Yoshizaki et al., 2024
2024	CRISPR/Cas9 sterile marine recipient development	Nibe croaker, <i>Nibea mitsukurii</i> ; cryopreserved testicular cells	dnd-knockout nibe croaker	Developed germ-cell-less marine fish recipients; transplanted recipients produced only donor-derived offspring through spontaneous mating.	Yazawa et al., 2024
2024	Xenotransplantation trial for eel reproduction	European eel, <i>Anguilla anguilla</i> ; fresh/thawed spermatogonia	Zebrafish, <i>Danio rerio</i> , and triploid European sea bass, <i>Dicentrarchus labrax</i>	Tested zebrafish and sea bass as potential recipients for eel spermatogonia; donor cells were injected but not detected in recipient gonads at later sampling, highlighting	Blanes-García et al., 2024



				compatibility barriers.	
2024	Adult recipient intrapapillary transplantation	Goldfish, <i>Carassius auratus</i> ; male germ cells / spermatogonia	Adult common carp, <i>Cyprinus carpio</i> , cytoablated by busulfan + heat	Donor spermatogonial cells colonized recipient testes and resumed spermatogenesis within about 8 weeks; useful for faster surrogate production.	Vigoya et al., 2024
2023	Large-bodied surrogate to enhance zebrafish sperm production	Zebrafish, <i>Danio rerio</i> ; spermatogonial cells from Tg(ddd4:egfp) males	Sterile giant danio, <i>Devario aequipinnatus</i>	Giant danio chimeras produced functional zebrafish sperm with ~3× higher volume and ~10× higher sperm concentration than donor zebrafish.	Nayak et al., 2023
2023	Germ-cell recovery, cryopreservation and transplantation in sturgeon	California white sturgeon, <i>Acipenser transmontanus</i> ; early-stage germ cells	Larval California white sturgeon	Developed donor selection, germ-cell isolation, cryopreservation and intraperitoneal transplantation strategy for conservation aquaculture of sturgeon.	Romney et al., 2023
2022	Surrogate broodstock in Scombridae	Chub mackerel, <i>Scomber japonicus</i> ; testicular cells	Germ-cell-less hybrid mackerel, female <i>S. australasicus</i> × male <i>S. japonicus</i>	Produced donor-derived chub mackerel sperm and eggs; some mature recipients spawned	Tani et al., 2022



				naturally and generated normal donor-derived hatchlings.	
2022	Genome-edited sterile salmonid recipient	Rainbow trout, <i>Oncorhynchus mykiss</i> ; donor germ cells	dnd-knockout rainbow trout	Generated germ-cell-less rainbow trout recipients; donor cells migrated to gonads and mature recipients produced only donor-derived sperm and eggs.	Fujihara et al., 2022
2022	Inter-order xenogeneic germ-cell transplantation for endangered mahseer	Semah mahseer, <i>Tor douronensis</i> ; frozen germ cells	Nile tilapia, <i>Oreochromis niloticus</i>	Produced donor-derived semah mahseer offspring at 14 months post-transplantation; first report of donor-derived offspring from inter-order germ cell transplantation.	Saleedang et al., 2022
2021	Small surrogate for common carp genetic-resource management	Common carp, <i>Cyprinus carpio</i> ; testicular germ cells	Goldfish, <i>Carassius auratus</i>	Goldfish surrogates produced pure common carp gametes and viable common carp progeny; useful for reducing broodstock-maintenance	Franěk et al., 2021



				cost and space.	
2021	Inter-family germ-cell transplantation in marine flatfish	Japanese flounder, summer flounder and turbot spermatogonia	Triploid Japanese flounder, Paralichthys olivaceus	Demonstrated colonization, proliferation and donor-derived functional sperm production within Pleuronectiformes; reported as a first inter-family breakthrough in marine fish.	Zhou et al., 2021
India's Case Study					
2023		Goldfish, Carassius auratus; germ cells from prepubertal male donors	Adult common carp, Cyprinus carpio; recipient germ cells depleted by busulfan + high temperature	Produced pure goldfish progeny from common carp surrogate parents. Donor-derived gametes were confirmed by PCR-RFLP, and artificial fertilization/induced spawning produced goldfish offspring. This is the strongest India-based surrogate-progeny study.	Majhi, 2023
2017		Not a donor-recipient transplantation study; recipient-preparation model	Adult common carp, Cyprinus carpio	Produced 100% germ-cell-depleted common carp using busulfan + high	Majhi et al., 2017



				temperature within 10 weeks; important for making sterile surrogate recipients.	
2016		Rohu, Labeo rohita; cryopreserved male/female germ cells	Catla, Catla catla	Tested transplantation worthiness of cryopreserved rohu germ cells. More than 70% germ cells remained viable, and transplanted cells colonized/proliferated in catla gonads; however, donor-derived offspring were not reported.	Patra et al., 2016
2015		Rohu, Labeo rohita, and catla, Catla catla; isolated germ cells	Catla, rohu, and common carp, Cyprinus carpio	ICAR-CIFA reported surrogate carp production through xenogeneic germ-cell transplantation. Rohu germ cells were transplanted into catla and vice versa; catla/rohu germ cells were also transplanted into common carp. The report stated donor-	Jayasankar / ICAR-CIFA, 2015, ICAR News



				derived gametes and 30–40% surrogate carp fry/fingerlings.	
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Challenges and Limitations

Despite its significant potential, surrogate broodstock technology faces several challenges, including the technical complexity of germ cell transplantation, limited success in marine species, production of sterile recipients, and ethical as well as regulatory concerns associated with genome editing. Furthermore, large-scale commercialisation requires standardised protocols, improved transplantation efficiency, and cost-effective methodologies.

Future Prospects

Integration of surrogate broodstock technology with genomics, cryopreservation, stem cell biology, and CRISPR/Cas9-based sterilisation is expected to accelerate genetic improvement and conservation in aquaculture. The technology holds strong potential for germplasm preservation, production of climate-resilient and high-value species, and precision breeding programmes. These advancements may substantially support sustainable aquaculture and aquatic biodiversity conservation.

Conclusion

Surrogate broodstock technology is an emerging reproductive biotechnology with significant potential in aquaculture for conservation, genetic improvement, selective breeding, and sustainable seed production. Successful applications across Japan, Europe, China, and India highlight its transformative role in donor-derived gamete production. Advancements in germ cell biology, cryopreservation, and genome editing are expected to further enhance their large-scale application for sustainable aquaculture and aquatic biodiversity conservation.



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