Artificial Wombs: Revolutionizing Neonatal Care and Beyond: Narrative Review

Aiysha Gul[1]*, Hytham Hummad[2], Andrea Nicole Abifaraj Daaboul[3], Vasudha Batta[4] Kathia Maria Quezada Reyes[5], Julio Cesar Orellana Rodríguez[6], Sandra Sofia Matta Perdomo[7], Raúl Alfredo Urbina Zuniga[8], Carlos Andrés Portillo Muñoz[9], Leslie Nicole Crosdaile Coello[10], Christian Eduardo Kafaty Abudoj[11]

[1]Department Of Obstetrics and Gynecology, Mardan Medical Complex, Pakistan

[2]Assistant professor Department of Anesthesia and Operations, College of Applied Medical Sciences- Khamis Mushait, KING KHALID UNIVERSITY, Abha, Kingdom of Saudi Arabia

[3]Department Of Medicine And Surgery, Universidad Catolica De Honduras, Honduras

[4]Department Of Medicine, Sri Guru Ram Das Institute Of Medical Sciences And Research, Amritsar, India

[5]Department Of Medicine And Surgery, Universidad Catolica De Honduras, Honduras
[6]Department Of Medicine And Surgery, Universidad Catolica De Honduras, Honduras
[7]Department Of Medicine And Surgery, Universidad Catolica De Honduras, Honduras
[8]Department Of Medicine And Surgery, Universidad Catolica De Honduras, Honduras
[9]Department Of Medicine And Surgery, Universidad Nacional Autónoma De Honduras, Honduras.
[10]Department Of Medicine And Surgery, Universidad Catolica De Honduras, Honduras
[11]Department Of Medicine And Surgery, Universidad Católica De Honduras "Nuestra Señora Reina De La Paz," Honduras

Corresponding Author*: Aiysha Gul

Abstract

Artificial womb technology (AWT) is a prominent innovation in neonatal care and reproductive health, whereby technical solutions for preterm births and future human reproduction are supplied. This paper outlines the history of AWT, the future AWT advancements, how AWT assists preterm infants, the integration of AWT with other assisted reproductive technology, and other social and ethical concerns about AWT. The specific nature of the research stems from the fact that the study combines the results of biomedical engineering, clinical observation, and ethical assessment to analyse AWT's current state, future, and potential.

We identified important evidence to support the effectiveness of AWT in maximising the positive impacts of preterm birth for infants and possibly eliminating further adverse effects due to mimicking the natural environment provided by the uterus. Expanding its usage to full ectogenesis and space travel includes widening interaction with technologies like in vitro fertilisation and gene editing. The study identifies key limitations, such as regulatory issues, risks and inequality barriers to accessing the procedure. Considerations of the ethical issues involved in the roles of parents, the legitimacy of fetal life, and the conventional sensibility of 'birth' further elucidate the essential frameworks AWT must build upon and be directed by.

Finally, AWT holds the promise of transformative potential but must navigate technical, ethical, and societal hurdles to integrate into healthcare systems successfully. Such complexities require timely scientific and stakeholder engagement regarding the anticipated dilemmas to optimise AWT's implementation for equality, safety, and consistent societal standards.

Keywords: *Artificial Womb Technology, Neonatal Care, Ectogenesis, Reproductive Health, Ethics, Biotechnology*

1. Introduction

Artificial womb technology (AWT) represents a groundbreaking development at the intersection of neonatal care, reproductive technology, and bioethics. Since the advent of in vitro fertilisation in the early 1980s, AWT has garnered scientific and ethical attention as researchers and clinicians explore its potential to revolutionise neonatal medicine (Bie et al., 2022). In recent years, advances in extracorporeal neonatal life support systems have revitalised this area of research, positioning AWT as a transformative innovation with profound implications for modern medicine (Bie et al., 2022; Segers & Romanis, 2022).

At its core, AWT, also known as artificial amnion and placenta technology (AAPT), seeks to replicate the critical functions of the human womb outside the body. Early research has demonstrated promising results in animal models, bringing the prospect of ex vivo gestation closer to clinical reality (Segers & Romanis, 2022). These breakthroughs suggest the potential for enhanced survival rates and long-term outcomes for premature infants who are currently at significant risk due to underdeveloped organs.

Historically, much of the discourse around AWT has been dominated by discussions of "complete ectogenesis," a hypothetical scenario in which human embryos are entirely gestated outside the maternal body. However, recent developments underscore the more immediate and practical applications of AWT. The focus has shifted toward its role in neonatal care, particularly for extremely premature infants, often called "detonates" (Bie et al., 2022). This shift is critical, as it reframes AWT not as a futuristic concept but as a technology with tangible potential to address current medical challenges.

The significance of AWT extends beyond its clinical applications. It also raises important ethical, legal, and societal questions. For instance, the moral and legal status of ex utero gestating entities remains a topic of robust debate. Additionally, researchers emphasise the necessity of a value-sensitive design approach, ensuring that AWT's development and eventual implementation align with societal values and ethical principles (Segers & Romanis, 2022). Addressing these issues is paramount to fostering public trust and ensuring equitable access to this technology.

In modern medicine, the emergence of AWT marks a paradigm shift in how premature infants are cared for and how prenatal interventions are conducted. AWT could enable novel therapeutic strategies by providing an environment miming the womb, from facilitating organ development to supporting surgical interventions during gestation. As the technology progresses, it has the potential to redefine the boundaries of neonatal and maternal-fetal medicine, offering new hope to families and healthcare providers alike.

This review article explores AWT's historical evolution, current advancements, and future implications. By synthesising the latest research, it seeks to highlight the profound impact of this technology on neonatal care and reproductive medicine. Additionally, the review will critically examine AWT's ethical and legal considerations, contributing to an informed and balanced discourse on its potential applications and limitations. Through this analysis, the article aspires to provide a comprehensive overview of AWT and its role in shaping the future of medicine.

2. The Science Behind Artificial Wombs

Artificial womb technology (AWT), also referred to as artificial placenta or ectogenesis, is a revolutionary innovation designed to support highly premature infants by replicating the physiological functions of the human uterus and placenta. Its ultimate goal is to create a controlled environment that supports fetal development outside the maternal body, offering new solutions to critical challenges in neonatal care (Bie et al., 2020).

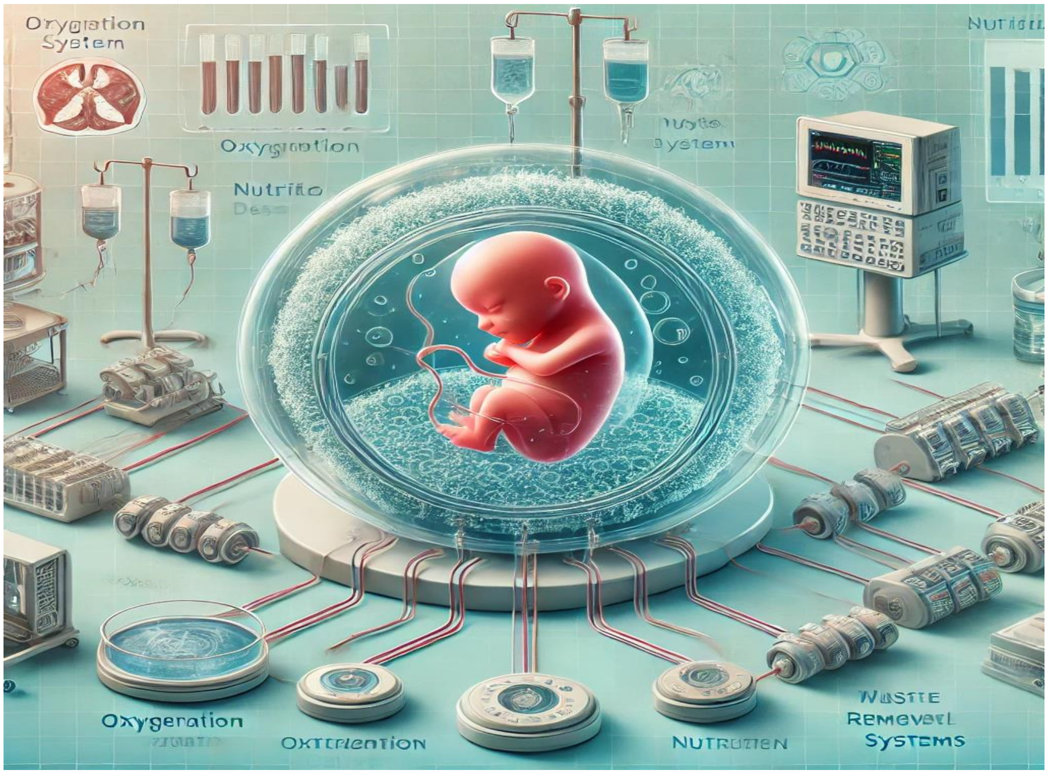

Figure 1: The artificial womb system

- **Definition and Components of an Artificial Womb**

At its core, an artificial womb system includes several integrated components aimed at mimicking the uterine environment:

1. **Fluid-Filled Biobag**: A flexible, sterile enclosure filled with a synthetic amniotic fluid designed to protect and cushion the fetus. This fluid also facilitates waste removal and provides essential nutrients.
2. **Oxygenation Systems**: Devices such as extracorporeal membrane oxygenation (ECMO) or other advanced gas exchange mechanisms deliver oxygen and remove carbon dioxide, emulating the natural gas exchange performed by the placenta.
3. **Nutrient Delivery Mechanisms**: These systems provide vital nutrients, hormones, and growth factors to sustain fetal development. Advanced peristaltic pumps and biomimetic interfaces ensure precise delivery tailored to the fetus's needs (Bie et al., 2020; Romanis et al., 2024).

These components work together to replicate critical aspects of intrauterine life, offering a life-saving alternative for extremely premature infants who are unable to survive in traditional neonatal incubators.

- **Key Technologies Involved**

Several cutting-edge technologies underpin artificial womb systems:

- **Biobags**: Initially developed for animal studies, biobags are transparent, flexible containers that provide a sterile, temperature-controlled environment for the fetus.
- **Extracorporeal Membrane Oxygenation (ECMO)**: This technology ensures efficient oxygen and carbon dioxide exchange, crucial for fetal survival and development.
- **Artificial Amniotic Fluid**: A carefully formulated fluid that mimics natural amniotic fluid's nutrient and hormonal content, supporting fetal organ development.
- **Fetal Monitoring Systems**: Advanced sensors measure fetal health metrics, including heart rate, oxygen levels, and growth parameters, enabling real-time adjustments to the artificial environment.

- **Current Experimental Models and Success Rates**

Recent experimental models have demonstrated substantial progress in validating the feasibility of AWT. Studies with animal models, particularly lamb fetuses, have shown significant success:

1. **The Philadelphia Biobag Model**: Developed by Flake et al. (2023), this model successfully maintained premature lambs for up to four weeks, demonstrating normal lung development and growth.
2. **Japanese Artificial Placenta System**: Researchers in Japan achieved similar results, with fetuses demonstrating organ maturity comparable to natural gestation (Segers & Romanis, 2022).

Despite these breakthroughs, challenges remain in adapting these systems for human use, including scaling the technology and addressing species-specific physiological differences.

- **Comparison to Natural Uterine Environments**

Replicating the natural uterine environment is a complex task beyond physical attributes. Key aspects include:

- **Physiological Differences**: While neonatal incubation supports neonatal physiology, ectogestation preserves fetal physiology, maintaining the functions of underdeveloped organs (Kingma & Finn, 2020).
- **Mereological Integration**: The natural uterus provides a dynamic interface between the maternal body and fetus, involving immune modulation and hormonal signalling that current models cannot fully replicate.
- **Risk Profiles**: Artificial wombs differ from traditional neonatal care in risk profiles, requiring careful monitoring to prevent complications like infection, inadequate oxygenation, or mechanical failure (Flake et al., 2023).

Table 1 below highlights key differences between natural uterine environments and artificial womb systems:

Aspect	Natural Uterus	Artificial Womb System
Gas Exchange	Placental diffusion	ECMO or similar oxygenation systems
Nutrient Delivery	Via maternal blood supply	Pumped nutrient delivery mechanisms
Immune Modulation	Maternal-fetal immune interactions	Limited or absent
Hormonal Regulation	Dynamic maternal hormonal changes	Synthetic hormonal supplementation
Waste Removal	Placental clearance	Artificial amniotic fluid circulation
Developmental Cues	Biochemical signals from the mother	Partially simulated

Artificial womb technology has made remarkable strides, offering hope for improved outcomes in neonatal care. However, the technology still faces significant hurdles in replicating the intricate dynamics of natural uterine environments. Bridging these gaps requires continued interdisciplinary collaboration, addressing technical challenges and ethical considerations

(Romanis et al., 2024; Segers & Romanis, 2022). As research advances, optimising AWT will be crucial for its eventual clinical application, ensuring it is a safe, effective, and equitable solution for premature infants.

3. Applications in Neonatal Care, Ethical and Societal Implications

Preterm birth remains a global health challenge, with approximately 15 million babies born prematurely each year, representing over one in ten live births (WHO, 2023). Among these, extremely preterm infants, particularly those born before 28 weeks of gestation, face significant medical challenges, including respiratory distress syndrome, intraventricular haemorrhage, and sepsis. Long-term complications are also prevalent, encompassing neurodevelopmental disorders such as cerebral palsy and cognitive delays, alongside an increased risk of chronic cardiovascular and metabolic conditions in later life (Jańczewska et al., 2023; Song, 2022). Despite advances in neonatal intensive care, survival rates for extremely premature infants vary significantly depending on geographical and socioeconomic factors. Moreover, current neonatal care approaches often expose infants to iatrogenic injuries, such as ventilator-induced lung damage and infections from invasive procedures, highlighting an urgent need for innovative solutions to improve outcomes for preterm infants.

Artificial womb technology (AWT) and artificial placenta (AP) systems represent a transformative approach to neonatal care by closely replicating the uterine environment and addressing the developmental needs of extremely preterm infants. Unlike conventional incubators, which support neonatal physiology, AWT emphasises maintaining fetal physiology, a critical aspect for those not yet prepared for extrauterine life (Bie et al., 2020). AWT eliminates the need for mechanical ventilation by providing a fluid-filled environment, significantly reducing the risk of bronchopulmonary dysplasia and other lung injuries. Furthermore, the continuous delivery of nutrients, hormones, and growth factors in a womb-like setting supports brain development, minimising the likelihood of neurodevelopmental impairments. AWT also creates a stable developmental environment by reducing exposure to external stressors and eliminating invasive procedures. These advancements collectively improve survival rates and long-term health outcomes, offering a promising solution for preterm infants while potentially alleviating the societal and economic burden of managing lifelong disabilities (Jańczewska et al., 2023).

The capacity of AWT to address key pathways leading to long-term health complications in preterm survivors is particularly noteworthy. For instance, by ensuring optimal oxygenation and nutrient delivery, AWT mitigates the risk of cardiovascular dysfunction commonly associated with preterm birth (Song, 2022). Similarly, the technology supports endocrine regulation by mimicking natural placental function, reducing the likelihood of metabolic disorders such as obesity and diabetes in later life. Additionally, artificial amniotic fluid can be tailored to include immunomodulatory factors, promoting robust immune system development. By addressing these risks comprehensively, AWT can potentially improve the quality of life for preterm survivors and significantly reduce healthcare costs associated with managing long-term complications.

The development of AWT and ectogenesis technologies has ignited complex ethical debates, particularly concerning fetal viability, abortion rights, and the moral status of the fetus. These technologies challenge existing legal and ethical frameworks by redefining the concept of viability, as the ability to sustain fetal development outside the maternal body could influence debates on abortion laws and reproductive autonomy (Segers, 2021). Furthermore, sustaining fetal life in an artificial womb raises questions about the moral and legal rights of the fetus, potentially complicating decisions about pregnancy termination or medical interventions. Ethical concerns also extend to equitable access, as ensuring that AWT is available across all socioeconomic strata is critical to avoid exacerbating existing healthcare disparities. These debates underscore the importance of developing robust ethical guidelines to balance scientific progress with respect for human rights and societal values.

The introduction of artificial wombs could profoundly alter traditional concepts of parenthood and gestational roles. Separating gestation from the maternal body challenges societal perceptions of motherhood and diminishes the role of biological ties as defining factors in parenthood. This shift raises legal and ethical questions about parental responsibilities during artificial gestation, particularly in cases involving medical complications or disputes over custody. Public perceptions of AWT will likely vary depending on cultural, religious, and ethical beliefs, necessitating targeted education and engagement to foster societal acceptance (Kennedy, 2020). Moreover, the detachment of pregnancy from the maternal body may influence emotional dynamics and bonding between parents and their children, highlighting the need for further research into the psychological and social implications of AWT.

Table 2 below outlines the key potential impacts of AWT on traditional reproductive and parenting paradigms:

Aspect	Traditional Paradigm	Potential Impact of AWT
Gestational Role	Exclusively maternal	Technologically mediated
Parental Bonding	It begins during physical pregnancy	May shift to post-birth bonding processes
Definitions of Parenthood	Often tied to biological gestation	Broadened to include non-gestational roles
Accessibility for Infertile Individuals	Limited options (e.g., surrogacy, adoption)	Expanded through ectogenesis
Cultural Symbolism of Childbirth	Deeply rooted in biological processes	Redefined by technological possibilities

Artificial womb technology has the potential to redefine childbirth and parenting, fundamentally altering societal views on reproduction. By eliminating the need for physical gestation, AWT could lead to new cultural and symbolic meanings of childbirth while broadening access to parenthood for individuals unable to conceive or carry pregnancies, such as same-sex couples, single parents, and those with medical conditions affecting fertility. However, this detachment of pregnancy from the maternal body raises questions about its impact on parent-child bonding, with potential psychological and social ramifications that remain underexplored. Addressing these implications through interdisciplinary research and inclusive public dialogue is vital as these technologies evolve.

Artificial womb technology offers a groundbreaking solution to the challenges associated with preterm birth, with the potential to improve neonatal survival rates and minimise long-term health complications. However, its development is accompanied by profound ethical, societal, and psychological questions that demand careful consideration. Addressing these challenges requires a balanced approach that integrates scientific innovation with robust ethical frameworks, equitable policies, and inclusive societal engagement to ensure that AWT is a transformative yet socially responsible advancement in neonatal care.

4. Navigating Regulatory and Safety Challenges and Expanding Implications of Artificial Womb Technology

The development and implementation of artificial womb technology (AWT) pose intricate regulatory and safety challenges that extend well beyond neonatal care. There is a noticeable void in specific regulatory frameworks tailored to AWT, necessitating reliance on existing guidelines for neonatal care and reproductive technologies. However, these guidelines are often inadequate for addressing the unique aspects of artificial gestation, highlighting the need for specialised policies to govern this technology's safe and ethical use (Bie et al., 2022; Segers, 2021).

One foremost concern is ensuring safety from preclinical studies to human trials. This process involves addressing substantial risks to both the fetus and, in cases involving transfer from a natural uterus, the pregnant individual. For instance, maintaining physiological integrity during transfer and mitigating potential complications such as infection or developmental disruptions are paramount (Segers, 2021). Ethical study designs are critical in this phase, requiring clear protocols and international consensus to ensure transparency, safety, and efficacy. Researchers and clinicians must collaborate with ethicists to develop guidelines prioritising patient and fetal welfare during the initial stages of human translation (Kukora et al., 2023).

Legal considerations for the widespread adoption of AWT also raise profound questions. The capacity of AWT to sustain fetal viability outside the maternal body challenges traditional definitions of life and viability, potentially affecting abortion laws and parental rights. Policies surrounding the moral and legal status of the fetus within artificial gestation systems will need to evolve, particularly in jurisdictions with strict reproductive laws or differing cultural norms. These issues are further compounded by debates about ownership, custody, and the responsibilities of intended parents in the context of artificial gestation (Horn, 2020; Segers, 2021).

Beyond its immediate application in neonatal care, AWT has far-reaching implications for reproductive choices and family planning. For individuals unable to conceive or carry a pregnancy, this technology could offer a groundbreaking alternative, enabling biological parenthood without gestation. Additionally, it holds the potential for addressing unintended pregnancies or medical conditions that render traditional gestation unsafe. Nevertheless, the separation of procreation from gestation raises ethical questions about the evolving nature of parenthood and family structures. These debates are further enriched by discussions on the societal and cultural impact of such a fundamental shift in reproductive practices (Kennedy, 2020; Kingma & Finn, 2020).

Table 3: Comparison of Natural Uterine Environment and Artificial Womb Technology

Characteristic	**Natural Uterine Environment**	**Artificial Womb Technology (AWT)**
Oxygenation	The placenta provides oxygen via maternal blood flow	Oxygenation systems mimic placental gas exchange
Nutrient Delivery	Nutrients delivered through the umbilical cord	Nutrient delivery mechanisms provide essential growth factors
Physical Environment	The amniotic sac provides cushioning and protection	A fluid-filled bio bag replicates the amniotic sac
Immune Protection	Maternal immunity shields the fetus	Limited immune support; risk of infection managed externally
Neurodevelopment	Maternal hormones and interactions influence brain development	Mimicked via controlled biochemical environments

AWT also presents unique opportunities for advancing scientific understanding of human development. By providing a controlled environment for fetal growth, researchers can gain unprecedented insights into fetal physiology, developmental milestones, and the influence of external factors on gestational progress. This could lead to breakthroughs in understanding congenital disorders, refining prenatal interventions, and enhancing early childhood health outcomes (Bie et al., 2020). Such a controlled setting might also allow for the testing of novel therapies and the development of predictive models for gestational health, paving the way for targeted medical innovations.

Interestingly, the potential applications of AWT extend beyond Earth, particularly in the context of space exploration and colonisation. Long-duration space missions present unique challenges to reproductive health, including the effects of microgravity and radiation on conception and fetal development. AWT could provide a viable solution by ensuring fetal development in a controlled environment, thereby addressing concerns about the continuation of human reproduction in extraterrestrial settings. While speculative, these applications underscore the versatility of AWT and its capacity to address emerging challenges in human adaptation and survival (Mhatre et al., 2021).

The journey toward the responsible development and implementation of AWT requires a holistic approach that integrates scientific innovation, ethical reflection, and public engagement. Policymakers, scientists, and ethicists must work collaboratively to establish robust regulatory frameworks that prioritise safety, equity, and inclusivity. Public discourse will also play an essential role in fostering societal acceptance and addressing misconceptions about the technology.

In conclusion, artificial womb technology is promising to improve neonatal care, reshape reproductive possibilities and expand our understanding of human development. However, these advancements come with complex regulatory, safety, and ethical challenges that demand interdisciplinary collaboration and careful navigation. By engaging diverse stakeholders and addressing these issues proactively, AWT can emerge as a transformative yet socially responsible innovation with profound implications for humanity (Segers, 2021; Sonko et al., 2024).

5. Future Prospects and Innovations in Artificial Womb Technology

The trajectory of artificial womb technology (AWT) reflects its potential to redefine reproductive medicine and neonatal care, advancing toward a vision of complete ectogenesis. Emerging technologies are enhancing AWT systems, with innovations in extracorporeal neonatal life support and bioengineered uterine environments offering unprecedented support for preterm infants. These advancements improve survival rates and ignite discussions about the broader implications of artificial gestation (Bie et al., 2022).

The integration of AWT with other reproductive technologies, such as in vitro fertilisation (IVF) and gene editing, signals transformative possibilities for human reproduction. This synergy could address genetic disorders and optimise fetal health, while speculative applications, such as cryopreserved embryos for extraterrestrial colonisation, further expand the horizons of AWT's utility. By combining gene editing and artificial gestation, humanity might envision controlled reproductive processes for specific environmental challenges, such as long-duration space travel or life on exoplanets (Edwards, 2021).

However, AWT's evolution is not without technical and societal challenges. Technical hurdles, such as replicating natural pregnancy's complex hormonal and immunological interplay, remain significant. The logistical demands of scaling AWT systems for widespread use will require substantial resources and interdisciplinary collaboration. Ensuring these systems are safe, reliable, and accessible to diverse populations presents an additional layer of complexity. Socioeconomic disparities could limit access to AWT, creating ethical dilemmas about who benefits from these technologies and exacerbating existing inequalities in healthcare systems (Hooton & Romanis, 2022).

The societal implications of AWT are equally profound as the line between fetal and neonatal physiology blurs, and traditional definitions of gestation and birth are being challenged. Questions surrounding the roles of biological parents, the concept of gestational motherhood, and the rights of intended parents will require careful consideration. Moreover, public concerns about the ethical and moral dimensions of separating gestation from the human body are likely to shape the acceptance and integration of AWT into society. Addressing misinformation and fostering informed public discourse will be essential to navigate misconceptions and promote understanding (Kingma & Finn, 2020).

Public perception is critical in determining the adoption of transformative technologies like AWT. While proponents highlight its potential to enhance reproductive autonomy and address unintended pregnancies, critics caution against potential misuse and the commodification of reproduction. The societal reception of AWT will depend on transparent communication, ethical governance, and efforts to ensure equitable access. Policymakers, ethicists, and healthcare professionals must work collaboratively to build trust and create a framework that aligns technological innovation with societal values (Kennedy, 2020).

In conclusion, AWT represents a groundbreaking frontier in reproductive medicine, promising to address challenges in neonatal care and redefine reproductive possibilities. However, its path to large-scale implementation is fraught with technical, logistical, and ethical challenges. Ensuring equitable access, addressing public concerns, and combating misinformation is critical for its successful integration into healthcare systems. As we move toward a future where complete ectogenesis may become a reality, robust ethical and regulatory frameworks will be indispensable to navigate the complex interplay of technology, society, and human reproduction (Bie et al., 2020; Bie et al., 2022).

Conclusion

Artificial womb (AWT) technology has the potential to revolutionise neonatal care and redefine human reproduction. AWT is promising for the preterm birth challenge, improving neonate survival rates and reducing long-term health complications in neonates by offering a controlled environment that replicates the natural uterus. Further integration with advanced reproductive technologies, such as in vitro fertilisation (IVF) and gene engineering, also add to its use, and uterine tube work and complete ectogenesis may one day be just a reality. However, technical, ethical, and societal challenges accompany such transformative potential, which have to be taken care of.

Replicating the complex processes of natural gestation, such as hormonal control, immune interactions, and nutrient delivery, remains an enormous technical challenge. However, for the development and large-scale implementation of AWT systems, robust interdisciplinary collaboration across biomedical engineering, obstetrics, and developmental biology will be needed. Just as important is ensuring that these systems reach the highest safety standards when used in human trials to protect both the mother's and fetus's health.

AWT's development and implementation are based on ethical considerations. However, the technology presents a host of moral questions about the fetus's status, what makes a person a parent, and the repercussions when the human body and gestation are separated. Important deliberations must be made regarding issues like equitable access, the possibility of socioeconomic disparity, and the reshaping of traditional family structures. It will be essential for building trust and responsible development and deployment of AWT that first transparent and inclusive dialogue is established among scientists, ethicists, policymakers and the public. The development of AWT is also dependent upon its societal perceptions and public acceptance. Then, AWT should be made all-inclusive and helpful to all by addressing misinformation and ensuring that technology progresses in conjunction with creating comprehensive regulatory frameworks that will strike the right balance between innovation and ethical protection. Orks that balance innovation with ethical safeguards, ensuring that AWT is accessible and beneficial for all.

Finally, AWT is found where scientific innovation bridges the gap to societal transformation. Unquestionably, its path forward requires treading a careful balance between technical innovation, ethical integrity and social engagement to realise its promise to improve neonatal care, potentially opening up reproductive possibilities. Paved with the participation of collaboration and guided by the principles of inclusion, AWT development will potentially pave a path towards a future where humans and technology coexist harmoniously, tackling critical healthcare problems and redefining the geography of human reproduction.

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