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Understanding Orangutan Reproduction: Biological Aspects, Climate Change, and Contaminant Exposure

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Abstract

Orangutans (*Pongo* spp.) are arboreal primates and the only great apes native to Asia. Reproduction is crucial for the survival and long-term viability of their populations. This review explores orangutan reproductive biology, focusing on key features and the potential effects of environmental change. Orangutan reproduction is characterized by delayed sexual maturation, long interbirth intervals, and intensive maternal care, reflecting a slow life history strategy. Male bimaturism results in flanged and unflanged morphs, each exhibiting distinct mating strategies affected by social context. Female reproductive strategies, including mate selection and resistance to coercive mating, play a critical role in reproductive outcomes. Climate change, through alterations in rainfall and temperature, is expected to affect food availability, potentially disrupting reproductive timing and reducing offspring survival. The increasing presence of nanoparticles is also considered an emerging threat, though data specific to primates remains limited. Conservation efforts have focused on habitat protection, conflict mitigation, and ex situ management, including rehabilitation and the management of captive individuals in zoos; however, cryopreservation remains largely unexplored.

Keywords: climate, conservation, nanoparticle, orangutan, reproduction

Introduction

Orangutans (*Pongo* spp.) are arboreal primates and the only great apes native to Asia. They share key characteristics with other great apes, including a robust physique, short legs, and elongated arms (Hermann, 2017; Russon, 2009). There are three extant species of orangutans: the Bornean orangutan (*P. pygmaeus*), the Sumatran orangutan (*P. abelii*), and the Tapanuli orangutan (*P. tapanuliensis*). The Bornean orangutan is endemic to Borneo, while the Sumatran and Tapanuli orangutans are endemic to Sumatra. Compared to the Bornean and Sumatran orangutans, the Tapanuli orangutan has been less extensively studied, as it was only recently recognized as a distinct species, having previously been considered a subpopulation of the Sumatran orangutan (Nater et al., 2017). All three species are currently classified as critically endangered (Ancrenaz et al., 2024; Nowak et al., 2024; Singleton, 2024).

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Despite being distinct species, all three orangutans exhibit a high degree of morphological similarity. The primary distinctions lie in their hair characteristics: Bornean orangutans have darker, brownish hair, while Sumatran orangutans tend to have lighter, reddish hair. These differences become more apparent under microscopic examination. Bornean orangutan hair shafts are flatter and contain centrally located columns of dark black pigmentation. In contrast, the hair shafts of Sumatran orangutans are more cylindrical with a smoother cuticular structure, making them more prone to breakage (Kuswanda, 2014). Sumatran and Tapanuli orangutans show no significant morphological differences; their distinction as separate species is based primarily on facial morphometrics and genetic evidence (Nater et al., 2017).

Reproduction plays a critical role in the survival and long-term viability of orangutan populations, especially given their slow life history traits and low reproductive rates. Hence, the present study explores the reproductive biology of orangutans, emphasizing key features and examining the potential effects of environmental change.

Review Methods

This review employed an exploratory and integrative approach to synthesize current knowledge on orangutan reproduction, behavior, and conservation challenges. A range of sources was consulted, including peer-reviewed journal articles, academic books, conservation reports, and assessments from organizations such as the IUCN (International Union for Conservation of Nature).

Relevant literature was identified through searches in academic databases (e.g., Google Scholar, PubMed) and by examining the reference lists of key publications. Search terms included “orangutan reproduction,” "*Pongo spp.*," “mating behavior,” and “orangutan threats.” Books were selected based on academic credibility, author expertise, and relevance to the biological and ecological dimensions of orangutan studies.

No rigid inclusion or exclusion criteria were applied. Instead, the selection prioritized scientifically reliable works that were thematically relevant and offered comparative or contextual insights into the three orangutan species (*P. pygmaeus*, *P. abelii*, and *P. tapanuliensis*). This review integrated anatomical, behavioral, ecological, and environmental perspectives, with particular emphasis on the effects of habitat disruption and climate change on reproductive outcomes.

Literature Review Results

Reproductive Anatomy

In orangutans, reproductive anatomy is subtle and not externally prominent. The testes are concealed within a small, dark-pigmented scrotal bulge covered with long red hair, with an average combined weight of 35.3 grams. Although comparable in absolute size to gorilla testes, they are proportionally larger relative to body weight, yet still smaller than those of most other primates.

Elevated plasma testosterone levels likely account for the pronounced sexual dimorphism and aggressive behavior observed. The penis, in its flaccid state, is obscured by the prepuce and is minimally visible amidst surrounding hair. When erect or extended, it measures approximately 4 cm and becomes more prominent. Its short length may hinder intromission in natural settings; however, the agility of orangutans enables various mating positions, often while suspended from branches. The seminal vesicles are sizable and consist of a single coiled, unbranched tube, in contrast to the more intricate structure observed in humans (Short, 1979).

Female orangutans do not exhibit prominent secondary sexual characteristics. Breast development primarily occurs in the later stages of the first pregnancy, while perineal swelling is minimal and evident only during pregnancy. The absence of visual mating signals may confer an adaptive advantage in dense forest habitats, characterized by limited visibility and infrequent male–female encounters. Vocal and possibly pheromonal cues likely play a crucial role in mate location and sexual signaling. The ovaries are relatively small, whereas the testes, though still small in absolute terms, are approximately eight times larger than the ovaries when adjusted for body size. These anatomical and behavioral traits suggest that sexual selection and visual genital signaling have had a limited effect on orangutan evolution (Short, 1979).

Sexual Maturity

Orangutans exhibit a slow life history pattern characterized by large body size, delayed reproductive maturity, infrequent breeding, and extended lifespan. Studies have shown that Bornean orangutans have longer interbirth intervals than Sumatran orangutans, despite similar lifespans and ages of sexual maturity under captive conditions (Anderson et al., 2008). Sumatran orangutans possess the longest known interbirth interval among mammals, with a median gap of at least 8 years between pregnancies, while Bornean orangutans average 7.6 years. Both male and female infants exhibit high survival rates prior to weaning (van Noordwijk et al., 2018). Moreover, female orangutans demonstrate a remarkable 94% survival rate until their first reproduction; the highest documented among wild mammals (Hermann, 2017; van Noordwijk et al., 2018). In the wild, the age at first reproduction in females is estimated at 14–15 years, which is later than that observed in captivity. Females can reproduce throughout their lives, with no evidence of reproductive senescence (Hermann, 2017; Shumaker et al., 2008).

Male orangutan maturation is characterized by sexual bimaturism, resulting in two adult reproductive morphs. “Flanged” males exhibit full secondary sexual characteristics, including larger body size, cheek flanges, and laryngeal sacs. In contrast, “unflanged” males show arrested development of these traits but retain fully functional primary sexual organs and fertility (Maggioncalda et al., 1999).

In the Sumatran population ("Suaq"), unflanged males significantly outnumbered flanged males, whereas the Bornean population ("Tuanan") showed the opposite trend. The annual rate of flange development among unflanged males was significantly higher in the Bornean population (11.4%) compared to the Sumatran population (1.7%). These differences suggest that developmental arrest is more pronounced among Sumatran orangutans (Dunkel et al., 2013). Nonetheless, the developmental arrest in unflanged males is not caused by dominance suppression or social aggression. Instead, it appears to be an adaptive mechanism to mitigate the physiological consequences of chronic stress and to maintain lower stress levels (Kralick & McGrath, 2021).

Reproductive Cycle

Orangutans lack visual cues indicating the phases of their ovulatory cycles, differing from other great apes (Graham, 1981). Menstrual bleeding is also not reliably detectable, making ovulatory cycle observation particularly difficult in wild populations. Studies of captive orangutans offer greater insight. In this regard, menstrual cycle lengths vary across individuals, ranging from 23 to 33 days. In one captive juvenile, early menstrual cycles are irregular, with intervals spanning 29 to 108 days, indicating adolescent sterility; wherein young females cycle hormonally but are not yet fertile (Shumaker et al., 2008). A more comprehensive study found that the average cycle length in captive orangutans is approximately 29.7 days (range: 22–42 days). Hormonal analysis revealed two distinct estrogen peaks: the first preceding ovulation mid-cycle, and a second, higher peak during the luteal phase. Progesterone levels typically peak 8–11 days after the mid-cycle estrogen surge (Durgavich et al., 2023).

The average interbirth interval for wild orangutans is 7.6 years (van Noordwijk et al., 2018). This extended interval is attributed to prolonged maternal amenorrhea during the offspring's extended dependence period, with weaning occurring around age 7 (van Noordwijk & van Schaik, 2005). While offspring become locomotory independent by age 3, they continue to share nests with their mothers until weaning (van Noordwijk & van Schaik, 2005). Orangutans' slow development and high survival rates, 94% of females surviving to first reproduction around age 15, are likely adaptive responses to their arboreal, solitary lifestyle and low-productivity habitats (Rijksen, 1978; van Noordwijk et al., 2018).

Mating Systems and Reproductive Behavior

Orangutans have a complex mating system, particularly marked by male–male competition arising from sexual bimaturism, which reflects distinct reproductive strategies. Flanged males exhibit more aggressive and territorial behavior, producing long calls that serve as territorial signals. These calls also function to attract nearby females, illustrating the “call-and-wait” strategy employed by flanged males (Kunz et al., 2023; Utami et al., 2002). The frequency of calls and the proportion of responses from flanged males increase with the number of receptive females and male competitors (Spillman et al., 2017). Flanged males also display dominant behaviors, with the highest-ranking individuals capable of displacing both subordinate flanged and unflanged males from ongoing associations and previously initiated mating attempts with females (Mitani, 1985; Scott et al., 2024). Male dominance hierarchies are not static but are continually renegotiated through vocal and physical confrontations, suggesting that male–male interactions are characterized by unstable competitive dynamics (Spillman et al., 2017).

Unflanged males adopt different reproductive strategies, often relying on opportunistic or less conspicuous tactics, particularly effective during male dominance instability (Banes et al., 2015; Kunz et al., 2023; Utami et al., 2002). Both flanged and unflanged males engage in forced copulations, though this behavior is especially prevalent among unflanged males (Fox, 2002; Knott et al., 2010; Kunz et al., 2023; Mitani, 1985). Forced matings involve female resistance, including vocal distress and physical struggle, while males may use biting, grabbing, or slapping to restrain them. Most copulations are initiated by males and occur in trees throughout the day, typically preceded by genital investigation.

Forced copulations tend to last longer than consensual ones, which are more commonly observed among adult–adult pairings (Knott et al., 2010; Mitani, 1985). Females rarely exhibit proceptive behaviors toward unflanged males and often resist mating attempts, particularly when they have weaned infants, an indication of higher fertility (Knott et al., 2010; Kunz et al., 2021). To counter forced mating, females employ strategies such as forming associations with flanged males, thereby reducing the likelihood of coercive encounters initiated by unflanged males (Fox, 2002). During their periovulatory (fertile) periods, females preferentially associate and copulate with dominant flanged males, with these interactions being more frequent and cooperative in nature (Knott et al., 2010). This underscores the role of female mate choice and suggests that spatial association functions as a female strategy to mitigate sexual coercion (Fox, 2002; Knott et al., 2010).

Reproductive success between flanged and unflanged males is difficult to generalize. In a Bornean population, flanged males were found to sire a larger proportion of offspring (69.57%) than unflanged males (23.91%), with reproductive success being relatively evenly distributed among the flanged males (Scott et al., 2024). Observations from Tanjung Puting National Park revealed that a dominant flanged male, Kusasi, fathered 75% of all offspring conceived during his period of undisputed dominance between 1995 and 2003, indicating strongly skewed reproductive success in favor of the dominant flanged male (Banes et al., 2015). Conversely, studies on Sumatran populations have shown that unflanged males fathered more offspring than flanged males (Utami et al., 2002).

Threats to Orangutans

All three species of orangutans are classified as critically endangered due to habitat loss, fragmentation, and poaching (Ancrenaz et al., 2024; Nowak et al., 2024; Singleton, 2024). Among them, the Bornean orangutan has the highest population density, with recent estimates indicating a total of approximately 55,000 individuals. However, this figure represents a sharp decline from the estimated 288,500 individuals in 1973 (Ancrenaz et al., 2024). The principal causes of this decline are widespread habitat loss and degradation resulting from plantation expansion and timber extraction (Voigt et al., 2018).

In addition to habitat loss, direct mortality from human–orangutan conflict and hunting contributes to population decline. Interviews with 5,000 villagers across 450 villages found that 73% of orangutan killings were for non-conflict-related reasons, with consumption being the primary motive (Davis et al., 2013). Another study estimated that between 2,383 and 3,882 orangutans were hunted and killed between 2008 and 2009 (Meijaard et al., 2011). A survey conducted across 512 villages in Kalimantan reported that 57% had observed a decline or local extinction of orangutans, while 65% anticipated further declines or extinctions in the near future (Abram et al., 2015).

Similar threats affect the Sumatran orangutan, whose population has also been severely impacted by habitat destruction, particularly due to land conversion for oil palm plantations. More than 60% of their critical habitat was lost between 1985 and 2007 (Meijaard et al., 2018). Current population estimates for Sumatran orangutans stand at approximately 14,613 individuals, with projections indicating a potential decline of 4,500 individuals by 2030 due to ongoing deforestation (Wich et al., 2016).

The Tapanuli orangutan is the most endangered of the three recognized species, with fewer than 800 individuals remaining, confined to an estimated 1,000 km^2 of upland forest. The current range of this species has declined by approximately 97.5% since the 1890s and around 95% since the 1940s (Meijaard et al., 2021). Their remaining habitat is increasingly threatened, with more than 20% already allocated for agriculture or composed of degraded, regenerating forest and agricultural mosaics. Additionally, another 8% of their habitat is projected to be affected by flooding and infrastructure development associated with a proposed hydroelectric project (Sloan et al., 2018).

Climate Change

One of the most pressing environmental threats in recent years is climate change. It has caused significant shifts in global temperature and precipitation patterns. Recent studies indicate a consistent global warming trend, with surface temperatures increasing by 0.18°C per decade over the past 50 years (Samset et al., 2023). This rise in temperature can lead to increased precipitation, although rainfall patterns are becoming increasingly unpredictable. It is predicted that tropical regions will experience heavier rainfall, while dry regions will face shorter drought periods (Malhi et al., 2021). In primates, rising temperatures and altered rainfall patterns can destabilize populations. For instance, in the gray mouse lemur of Madagascar, population dynamics have been affected (Ozgul et al., 2023). Dry conditions and El Niño events have delayed birth seasons and reduced birth rates in some Neotropical primates (Wiederholt & Post, 2011).

Although no studies have examined the direct effects of climate change on orangutan reproduction, it might affect them indirectly by altering food availability. Changes in temperature and rainfall can affect plant physiological and metabolic processes, thereby influencing growth and productivity (Malhi et al., 2021). A study in tropical rainforests found a decline in the proportion of flowering and fruiting tree species over a 35-year period (1976–2010), coinciding with rising temperatures and increased rainfall. Furthermore, 57% of *Dipterocarpaceae* species, key components of Southeast Asian rainforests, rely on drought and low temperatures to trigger flowering. Climate change has reduced the frequency of these environmental cues, disrupting reproductive events in these plants (Numata et al., 2022). This situation demonstrates how climate change can reduce fruit availability and trigger cascading effects through the food web, potentially affecting frugivorous primates like orangutans.

Research on orangutans indicates that nutrient and food resource availability significantly shape reproductive timing. In provisioned or high-quality habitats, orangutans tend to reproduce earlier and have shorter interbirth intervals (Galdikas & Ashbury, 2012). Vogel et al. (2015) compared two Bornean orangutan populations in Tuanan and Sabangau and found that Tuanan orangutans, benefiting from higher fruit availability and better nutritional quality, achieved significantly higher daily caloric intake. This improved energy balance supports higher metabolic demands and may explain the higher population density observed in Tuanan. These findings support the hypothesis that habitats with greater fruit availability sustain higher reproductive output over time. A positive correlation between orangutan population densities and fruit availability has also been observed in Sumatran orangutans (Marshall et al., 2009).

This pattern is not limited to orangutans. A study of blue monkeys (*Cercopithecus mitis stuhlmanni*) found that limited access to energy-dense foods during seasonal scarcity led to heightened physiological stress in females, especially during late pregnancy and early lactation, resulting in delayed reproduction and longer interbirth intervals (Foerster et al., 2012). Similarly, research on white-headed langurs (*Trachypithecus leucocephalus*) showed that reproductive cycles correlate with environmental seasonality, with conceptions peaking during the rainy season and births during the dry season (Jin et al., 2009).

Food resource availability also affects orangutan nurturing behavior. The period of maternal dependency differs between Sumatran and Bornean orangutans, with Bornean immatures becoming independent by 5 to 7 years old, while Sumatran immatures stay close to their mothers until 8 to 10 years old and continue visiting thereafter. These differences likely reflect adaptive responses to ecological stressors (van Noordwijk et al., 2009). Longer parental bonds in Sumatran orangutans may be a response to higher predation risks, whereas earlier independence in Bornean orangutans could help reduce competition for resources. Sumatran immatures also reach adult-level feeding rates 2 to 3 years later than their Bornean counterparts, consistent with their higher dietary complexity and later weaning (Schuppli et al., 2016). This is supported by findings that Sumatran forests offer more consistent fruit availability throughout the year than Bornean forests, where periods of low fruit availability are more frequent and prolonged (Marshall et al., 2009). These patterns underscore how food availability affects orangutan survival and reproduction and highlight how climate change can affect orangutans indirectly by decreasing food resources.

Nanoparticles

In recent years, nanoparticles have emerged as a significant environmental concern. Mining activities, especially for metals like gold and rare earth elements, are major sources of nanoparticle release. These particles are produced through various mechanical processes, such as drilling, blasting, and ore processing, as well as through extraction, combustion, and waste disposal (Fan & Liu, 2021). Nanoparticles can bind to or dissolve toxic elements such as arsenic, lead, and mercury, and may be transported over long distances via river systems and the atmosphere (Silva et al., 2021). Advanced electron microscopy has revealed that mining can produce metal oxide nanoparticles (MONPs) as small as 2 nm, including elements like aluminum and titanium (Oliveira et al., 2022). The degradation of plastics into micro- and nanoparticles (MNPs) also contributes to environmental risks. Moreover, exposure to UV radiation and reactive oxygen species accelerates plastic breakdown, producing nanoparticles (Qin et al., 2022).

These particles can harm male reproductive health by crossing the blood–testis barrier and accumulating in reproductive tissues. They induce oxidative stress through the overproduction of reactive oxygen species (ROS), damaging DNA, proteins, and membranes. This stress impairs the function of Sertoli and Leydig cells, reduces sperm quality and viability, and disrupts hormone regulation, particularly testosterone production. Chronic exposure may lead to reduced fertility and a heightened risk of reproductive failure (Peng & He, 2024; Vassal et al., 2021). In females, nanoparticles may accumulate in the ovaries and uterus, causing structural and functional impairments. They may lead to hormonal imbalances, increased oxidative stress, and inflammation, apoptosis, or necrosis in ovarian tissues. Reported outcomes include polycystic ovary syndrome, follicular atresia, and reduced oocyte quality and fertility (Dianová et al., 2022; Peng & He, 2024).

Although most findings are from animal studies, they raise serious concerns for endangered wildlife, including orangutans. A comparative study on pregnant mice and non-human primates revealed that semiconductor nanoparticles could cross the placental barrier and accumulate in fetal tissues. In macaques, nanoparticle exposure significantly increased miscarriage rates to 60%, compared to a baseline of 15%. Although fetal organs showed no visible damage, signs of acute liver injury suggested that systemic maternal stress or inflammation contributed to pregnancy loss (Ye et al., 2019).

Orangutans, which rely on forest vegetation, may be exposed to nanoparticles through contaminated plants or water, inhalation of airborne particles, or dermal contact in polluted environments. Climate change exacerbates these risks by altering the environmental distribution and mobility of pollutants. Extreme weather events increase the release, transformation, and spread of contaminants. Heavy rainfall and runoff may mobilize buried pollutants into aquatic systems, while drought, soil erosion, and wildfires can distribute airborne nanoparticles over large areas (Bolan et al., 2024). Plants can absorb nanoparticles through roots or leaves, which are then transported via the vascular system to stems and foliage (Djanaguiraman et al., 2024). Consumption of these contaminated plants may introduce toxins into the orangutan's system. This is particularly concerning for females, who require sufficient nutritional intake to maintain reproductive cycles, support pregnancies, and ensure fetal development.

Conservation and the Future of Orangutans

Orangutan conservation efforts primarily focus on in situ strategies, particularly habitat protection and the mitigation of human-orangutan conflicts. Habitat protection is vital for ensuring the survival of orangutans in the wild and is generally more cost-effective compared to ex situ approaches, such as reintroduction programs. One approach to preserving the quality and integrity of orangutan habitats is the practice of sustainable logging, which balances environmental, wildlife, and community needs, thereby promoting fair income generation while preserving forests (Wilson et al., 2014).

In addition to habitat preservation, mitigating human-orangutan conflict is equally important, as such conflicts pose significant threats to orangutan populations. Community engagement and outreach programs are essential for educating local residents on practices that reduce the likelihood of conflict. Deterrent methods, including noise deterrents, traditional crop guarding, tree barrier nets, and orangutan-safe fencing, have proven helpful in preventing crop raiding by orangutans (Campbell-Smith et al., 2012; Sitompul et al., 2024; Suhardono et al., 2024). The construction of buffer zones between orangutan habitats and human settlements is also recommended, along with planting food trees near conservation areas and cultivating crops less attractive to orangutans near human settlements (Kuswanda et al., 2020; Seiler & Robbins, 2015).

It is critical to raise awareness about the ecological and ethical importance of orangutans, emphasizing their right to coexist within their natural habitats. Programs such as rehabilitation campaigns, compensation for crop damage, and the development of alternative livelihoods can further reduce conflict. Additionally, ecotourism may foster positive community attitudes toward orangutan conservation (Kuswanda et al., 2020; Maskulino et al., 2021; Sitompul et al., 2024). To ensure the effectiveness of in situ conservation strategies, conducting cost-benefit analyses of implemented actions is essential. Such analyses enable the strategic allocation of resources and help optimize conservation outcomes (Morgans et al., 2019; Santika et al., 2022).

Although habitat protection remains a crucial aspect of conservation, these efforts alone have not been sufficient to halt population declines. Orangutans are still projected to face localized extinctions (Abram et al., 2015). Therefore, ex situ conservation plays a critical role as an insurance strategy. It provides a safety net against extinction and serves as a reservoir for future reintroduction initiatives (Oklander et al., 2024). The success of ex situ programs depends on maintaining demographically and genetically viable populations to preserve genetic diversity and minimize inbreeding, which are essential to species survival (Pastrana et al., 2021).

Zoos and specialized facilities contribute to these efforts through captive breeding and genome banking. The ex situ population included 391 Bornean orangutans and 250 Sumatran orangutans, managed across five population management programs (Ancrenaz et al., 2024; Singleton et al., 2024). Despite the number of facilities maintaining ex situ orangutan populations, there has been a noticeable lack of published research on biobanking strategies specific to this genus (Sushadi, 2023). Kinoshita et al. (2021) provided valuable insights into the seminal characteristics of Bornean orangutans, revealing that sperm motility remains significantly longer in the coagulum fraction compared to seminal plasma (over 18 hours). This finding suggests that the coagulum may act as a natural medium preserving sperm viability post-ejaculation, offering potential for optimizing artificial insemination (AI) protocols.

Zainuddin et al. (2022) assessed the cryopreservation potential of orangutan semen, concluding that electroejaculation-collected samples are generally suitable for assisted reproductive technologies (ART). Their findings included a mean total motility of 61% and an average sperm viability of 77.75%. Although a relatively high rate of morphological abnormalities (*teratozoospermia*) was observed, post-thaw analysis still indicated viable sperm, with an average motility of 5% and viability of 43.88%. Furthermore, adult males with flanged status and larger testicular volume exhibited superior post-thaw semen quality. These studies underscore the importance of understanding orangutan semen characteristics to advance conservation through germplasm preservation and ART development. While various ART methods, including in vitro fertilization, have been explored in orangutans, their practical application remains extremely limited. To date, only one successful birth has been reported (Hall, 2014; Joslin et al., 1995).

Conclusion

Research on orangutan reproduction demonstrates that the reproductive strategy of this species is significantly affected by a combination of biological, ecological, and social factors. Bimaturism, prolonged birth intervals, and strong maternal dependency reflect a slow-life strategy developed in response to challenging environmental conditions. However, climate change and exposure to environmental contaminants, such as nanoparticles, further complicate the sustainability of orangutan reproduction. Climate change may affect food availability, while pollutants could impair reproductive quality through physiological mechanisms that require further investigation. Therefore, conservation efforts must extend beyond basic habitat protection to encompass a comprehensive approach integrating reproductive biology, population dynamics, and human-related influences. Ultimately, the survival of orangutans will depend on how effectively research, conservation strategies, and public awareness can be aligned to address these escalating challenges.

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