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RESEARCH

Impact of early and late maturation on the reproductive performance broodstocks of Russian sturgeon (*Acipenser gueldenstaedtii*)

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Abstract
This study investigates the reproductive viability of Russian sturgeon (*Acipenser gueldenstaedtii*) in aquaculture settings, focusing on the impact of maturation timing on breeding success and reproductive performance. Hormone-induced spawning was employed, and gamete quality was evaluated to compare two distinct maturation groups: Early-Maturing (EM, 10 + years) and Late-Maturing (LM, 20 + years). Both groups received identical hormone doses for induced spawning. However, the LM group demonstrated significantly lower spawning capability, achieving only 50.24% fertilization success compared to 85.09% in the EM group. Similarly, the hatching rate in the LM group averaged 40.4%, while the EM group achieved a markedly higher rate of 78.55%. Gamete quality also varied between the groups. The LM group exhibited larger egg diameters (3.58 mm) but lower relative fecundity/kg BW (950 eggs/kg), whereas the EM group had smaller egg diameters (2.97 mm) but significantly higher relative fecundity/kg BW (1210 eggs/kg). This study highlights the importance of considering maturation timing in sturgeon breeding and underscores the need for further research to fully understand the reproductive dynamics associated with maturation timing. Thus, broodstock management will contribute to farms producing more efficiently and economically.

Keywords Maturation timing · Gamete quality · Spawning success · Reproductive efficiency · Egg quality

Highlights
- Investigated how different sexual maturation ages (10 + vs. 20 + years) influence reproductive performance in Russian sturgeon under aquaculture conditions.
- Identified significant differences in fertilization and hatching rates between early- and late-maturing broodstock.
- Demonstrated age-related variation in egg quality, including egg diameter and relative fecundity per body weight.
- Provided practical recommendations for broodstock selection in sturgeon hatcheries to enhance breeding efficiency and sustainability.

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Introduction

Sturgeon species, particularly the Russian sturgeon (*Acipenser gueldenstaedtii*), hold significant ecological and economic value. Despite their importance, sturgeons have faced severe population declines due to overfishing, habitat destruction from dams and barriers, and pollution, pushing many species toward endangerment. In response, aquaculture has emerged as a critical tool for preserving these species and meeting commercial demands, especially for high-value products such as caviar and meat (Williot et al. 2001; Bronzi and Rosenthal 2014).

The Russian sturgeon, classified as a late-maturing species, is known for its delayed sexual maturation, with females typically reaching reproductive maturity between 6–10 years under aquaculture conditions (Hurvitz et al. 2005; Atre et al. 2021). This extended maturation period poses significant challenges for breeding programs, making it essential to investigate how age and maturation timing affect reproductive performance and gamete quality. Previous research highlights the importance of gamete quality, as it is closely tied to the overall health and reproductive success of broodstock (Safronov et al. 2022). While Safronov et al. (2022) focused on reproductive traits and offspring survival among Russian sturgeon from different rearing origins, our study differs by directly comparing reproductive outcomes—such as gamete quality, fertilization, and hatch success—between two defined age groups (10 + vs. 20 + years) maintained under identical aquaculture conditions. While age-related declines in reproductive success have been observed in various species, the relationship between early versus late maturation and its impact on gamete quality and fertility in sturgeon remains underexplored.

Reproductive output in fish is known to be influenced by age and body size, with fecundity generally increasing as individuals grow. However, this increase does not necessarily continue linearly throughout life. For instance, Van Eenennaam et al. (1996) showed that relative fecundity in Atlantic sturgeon peaked at 21–23 years of age (19.02 thousand eggs/kg) and slightly declined in older fish (18.89 thousand eggs/kg in the 24–29 year group), suggesting a potential onset of reproductive senescence. Similarly, Chen et al. (2022) noted that older fish may experience reduced reproductive efficiency due to skipped spawning cycles or oocyte resorption. Moreover, geographic variation affects maturation age; for example, Atlantic sturgeon mature as early as 5 years in southern U.S. rivers but as late as 34 years in northern populations (NOAA Fisheries 2024). Although these studies provide foundational insights into age-related reproductive patterns, few have directly compared early- and late-maturing sturgeon under controlled aquaculture conditions, particularly regarding gamete quality, fertilization success, and larval viability. Our study addresses this gap by comparing reproductive outcomes between 10 + and 20 + year-old Acipenser broodstock, and reveals that younger fish produced higher-quality gametes and achieved significantly better fertilization and offspring survival.

This study aims to investigate the reproductive performance of Russian sturgeon across two distinct maturation groups: Early-Maturing (EM, 10 + years) and Late-Maturing (LM, 20 + years). This study seeks to provide insights into the impact of maturation timing on sturgeon breeding performance by assessing gamete yield, quality, and reproductive outcomes across these two age groups. The findings will contribute to refining breeding practices in sturgeon aquaculture, promoting the use of sturgeon that exhibit optimal reproductive efficiency based on their maturation age.

Materials and methods

Study design

The study was conducted at the Aquatic Vertebrate Live Experiment Unit (İÜSUCAN) of the Faculty of Aquatic Sciences, Istanbul University. Two age groups of Russian sturgeon (*Acipenser gueldenstaedtii*), classified as Early-Maturing (EM, 10 + years) and Late-Maturing (LM, 20 + years), were used in this experiment.

Two tank systems were utilized: wintering tanks (cylindrical, 1.5 m deep, 3.5 m in diameter) and large concrete ponds (249 m^2, 286.3 m^3). Initially, broodstock individuals were maintained in the concrete ponds, which were supplied with a mixture of stream and underground water. Following the identification of mature candidates for the breeding season, selected individuals were transferred to wintering tanks with temperature-controlled underground water. A total of 12 males and 12 females from each age group (n = 24 per group) were placed in cylindrical wintering tanks with a volume of approximately 15 m^3. With an average body weight of ~ 10 kg, the stocking density in these tanks was approximately 8 kg/m^3—well below the recommended 20–25 kg/m^3 for overwintering Russian sturgeon (Chebanov and Galich 2013). The larger concrete ponds (286.3 m^3) used for long-term holding housed over 200 individuals averaging 15 kg in body weight, corresponding to a stocking density of ~ 10 kg/m^3. These low densities were maintained to minimize environmental stress and ensure comparable conditions across groups.

To mimic natural reproductive cues, the fish were maintained in wintering tanks at temperatures below 7 °C for a period of two months, simulating overwintering conditions. After this period, the water temperature was gradually increased to spawning levels (approximately 14–16 °C), and the fish were then transitioned into normal seasonal aquaculture environments. Both age groups underwent identical hormonal induction protocols to initiate spawning under standardized aquaculture conditions. The aim was to compare gamete quality, fertilization success, hatching rates, and overall reproductive performance between the EM and LM groups. Physicochemical water parameters during the holding and wintering phases are summarized in Table 1.

Fish were selected based on sexual maturity using an ultrasound imaging system. Each fish was individually tagged using passive integrated transponder (PIT) microchips (Biomark, USA), which recorded sex and age information. All fish were initially held in concrete ponds and later, 12 males and 12 females from each age group were transferred to the wintering tanks.

The broodstock individuals used in this study originated from a single aquaculture facility to ensure genetic consistency. LM group consisted of individuals hatched from fertilized

Table 1 Water quality parameters

Parameters	Concrete ponds Mean ± SD (Min–Max)	Wintering tanks Mean ± SD (Min–Max)
Temperature (°C)	12 ± 1.5 (10–14)	6 ± 0.5 (5–7)
Dissolved oxygen (mg/L)	8 ± 0.8 (7–9)	9 ± 0.6 (8–10)
pH	7.5 ± 0.2 (7.3–7.7)	7.5 ± 0.2 (7.3–7.7)

Dissolved oxygen, pH, and temperature were measured daily using portable multi-parameter probes. The values shown in the table represent weekly averages calculated over the course of the experimental period

eggs brought from the Krasnodar Research Institute of Fisheries (Russia) to the Sapanca Inland Water Research and Application Unit, Istanbul University, on January 13, 2001. EM group was derived from fertilized eggs (newly hatched larvae) obtained from the Center of Selection and Genetics for Aquaculture, Krasnodar, in May 2010. Both groups were reared at the same facility under identical environmental and nutritional conditions from larval stage onward, and no mixing of different origin populations occurred.

Broodstock were fed a formulated diet containing 45% protein, 12% lipid, 20% carbohydrates, and 13% ash, meeting the known nutritional requirements of sturgeon species. Feeding was discontinued during the wintering period, in accordance with standard protocols (Chebanov 1996; Chebanov and Galich 2013). Stocking densities were maintained within the recommended limits outlined in sturgeon aquaculture literature (Chebanov and Galich 2013).

This study was conducted during the 2022 reproductive season, covering a single spawning cycle. Broodstock were transferred to the wintering tanks in early winter as part of the routine breeding protocol, and the experiment continued through the spawning and fertilization phases. The age of each fish was determined based on documented hatch dates and institutional rearing records, as all individuals had been continuously reared at the Sapanca Inland Water Research and Application Unit since hatching. EM group consisted of fish hatched in 2010, while LM group included fish hatched in 2001. These records ensured accurate age classification and consistent traceability throughout the study.

Gamete collection and examination

In this study, sperm quality parameters such as motility, velocity, pH, spermatocrit, and sperm concentration were evaluated using pooled sperm samples obtained from three Early-Maturing (EM) males. Fertilization was carried out using a standardized volume of this pooled sperm to ensure consistent fertilization conditions across all treatments. The pooling approach minimized individual male variability and allowed for a reliable comparison of female reproductive performance. The spermatocrit value was used as an indirect indicator of sperm concentration, following protocols outlined by Chebanov and Galich (2013).

Eggs and sperm were collected throughout the breeding season (May) and were regularly monitored. Eggs were obtained via biopsy and assessed for the polarization index (Chebanov and Galich 2013). The total number of eggs per female was estimated by weighing the total egg mass and calculating the number based on the average weight of a known quantity of eggs. Egg size was determined by measuring 30 randomly selected eggs per female using digital calipers, and the average egg diameter was calculated accordingly. Sperm samples were collected from three EM males using a catheter, without anesthesia. The three EM males used for sperm collection had a mean body weight of 4000 ± 80.82 g and a mean total length of 90 ± 5.64 cm, which are within the typical range for reproductively mature Russian sturgeon in aquaculture (Chebanov and Galich 2013). Collection was performed immediately before the stripping of females to ensure freshness and consistency. Following collection, sperm quality and motility were assessed microscopically. Samples were stored at 4 °C in sterile containers for no longer than two hours prior to fertilization. This protocol ensured the use of viable sperm while minimizing variability due to male gamete condition. Sperm quality was evaluated using the Computer-Assisted Sperm Analysis (CASA) system. The CEROS II system from Hamilton-Thorne in Beverly, Massachusetts, USA, was utilized for evaluating spermatozoa motility characteristics. This system

was linked to an Olympus CX41 microscope operating at 12 °C. For sperm analysis, the CASA system employed the Animal Motility II software, recording videos at 60 frames per second through a Tokyo U-TV1X-2 digital camera with Hamilton configuration settings optimized for sturgeon analysis.

Hormone application

Hormonal induction was carried out during May 2022, in alignment with the natural spawning period. Gonadal readiness was confirmed via ultrasound imaging and polarization index evaluation. Anesthesia was not used during hormone injections; however, it was applied later during the stripping of females to reduce handling stress and ensure animal welfare. Once the polarization index indicated readiness for spawning, male and female broodstock underwent hormone treatments. Carp pituitary hormone (4 mg/kg body weight) was administered to both sexes, following established protocols (Chebanov and Galich 2013). Males were injected a single dose, while females were injected two doses. After 36 h from the first hormone application, fish were spawned, and eggs and sperm were collected for further analysis.

Fertilization and Incubation

Fertilization was conducted using hatchery water maintained at 13–14 °C. The fertilization procedure followed standardized protocols where 5 ml of sperm was mixed with 100 g of eggs to ensure a controlled sperm-to-egg ratio (Chebanov and Galich 2013). After fertilization, the stickiness of the eggs was removed by gently rinsing them with a 0.05% tannin solution for 1–2 min, followed by thorough washing with hatchery water. Fertilized eggs were then incubated in the Jugar incubation system, specifically designed for sturgeon eggs. Three replicates of Jugar were used for each broodstock group to maintain consistency and reliability in incubation conditions.

Assessment of reproductive success

The Leica S8 APO stereomicroscope equipped with Apochromatic Optics from Leica Microsystems (Switzerland) Ltd., along with a Leica DFC290 microscopy camera from Germany running the LAS Version 2.8.1 software (Build: 1554), was utilized for microscopic examination of eggs. Fertilization rates were determined within 24 h post-fertilization based on zygote identification, while hatching and survival rates were monitored daily during the incubation period. Representative images of unfertilized eggs and embryos at 24 and 48 h post-fertilization from both EM and LM groups are shown in Fig. 1 to provide visual comparison of developmental morphology. All metrics were calculated following standard procedures.

Statistical analysis

The results were presented as mean values along with the corresponding standard deviations (± SD). Data analysis was conducted using IBM SPSS software, version 28.0 for Windows. To compare reproductive and biometric parameters between the Early-Maturing

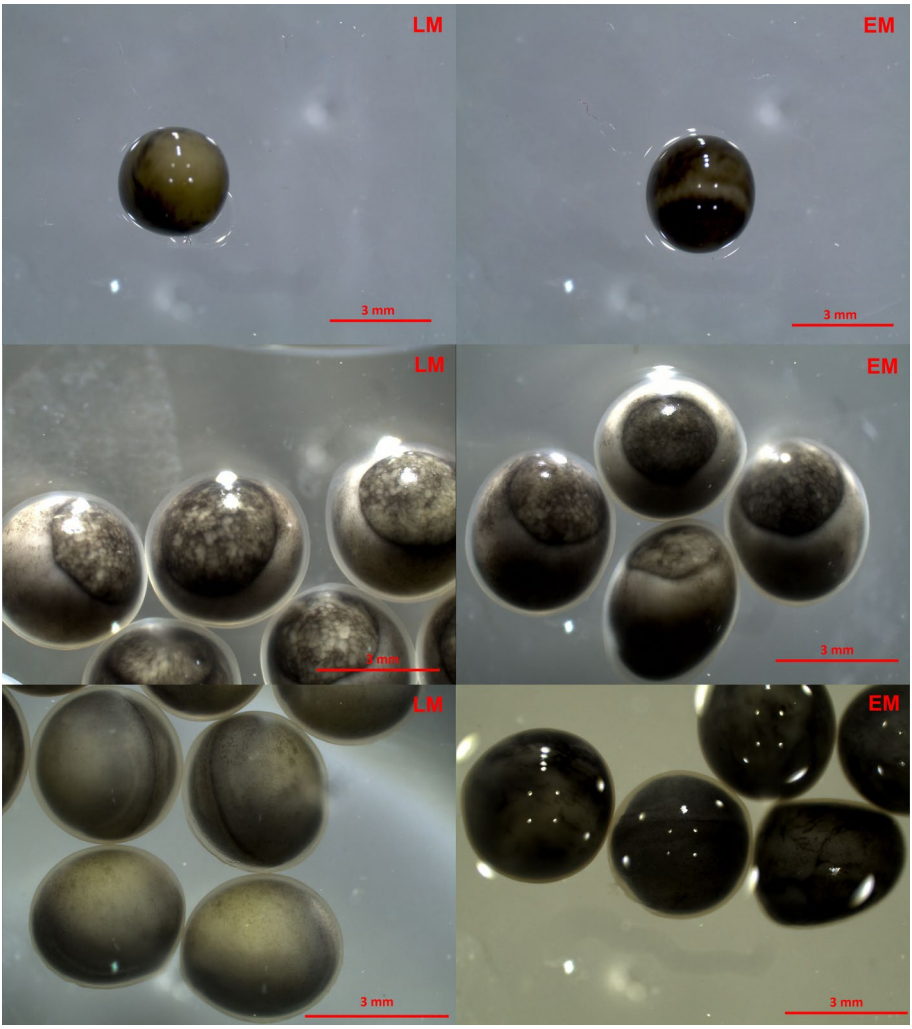


Fig. 1 Representative images of unfertilized eggs and developing embryos at 24 and 48 h post-fertilization from Late Maturation (LM; left column) and Early Maturation (EM; right column) groups. The top row shows unfertilized eggs, the middle row displays embryos at 24 h, and the bottom row shows embryos at 48 h

(EM) and Late-Maturing (LM) groups, an independent samples t-test was applied. Analyzed variables included body weight, body length, egg mass, relative fecundity (eggs/kg), total number of eggs, number of eggs per gram, egg diameters, fertilization success, and hatching rate.

Prior to the t-test, Levene's test was used to evaluate homogeneity of variances. In cases of unequal variance ($p < 0.05$), Welch's t-test was applied. Statistical significance was set at $p < 0.05$ with a 95% confidence interval. Significant differences between the groups were indicated in tables using letters:'a'for statistically significant differences and'b'for non-significant differences.

Table 2 Mean ± SD of sperm quality parameters from three Early-Maturing (EM) male Russian sturgeon used for pooled fertilization across all female groups

Parameters	Value
Weight (g)	4000 ± 800.82
Length (cm)	90 ± 5.64
Sperm volume (ml)	37 ± 7.12
Spermatocrit (%)	5.5 ± 0.17
pH	8.5 ± 0.1

Sperm samples from three EM males were pooled and used uniformly for fertilizing all females (both EM and LM groups). Therefore, no statistical comparison was made between male groups

Table 3 Sperm kinematic parameters (mean ± SD) of Early-Maturing (10 + years) male sturgeons used for pooled fertilization

Parameters	Value
VAP	79.66 ± 2.96
VSL	70.87 ± 2.01
VCL	98.58 ± 7.44
STR	89.26 ± 1.82
LIN	77.79 ± 4.06
ALH	5.43 ± 0.64
Total motility (%)	58.05 ± 5.04
Progressive motility (%)	22.68 ± 2.23

Data were obtained from three EM males. Sperm samples were pooled into a single batch to standardize fertilization and eliminate male-related variability. No statistical comparisons between groups were performed

Results

Sperm quality

The evaluation of sperm quality across three Russian sturgeon males revealed consistent patterns in biometric and reproductive traits (Table 2). The total sperm volume collected per male averaged 37 ± 7.12 mL, while the spermatocrit—reflecting the proportion of sperm cells within the milt—was 5.5 ± 0.17%. The sperm pH was 8.5 ± 0.1, indicating a slightly alkaline environment that is typical for sturgeon sperm and critical for maintaining motility and fertilization potential. The mean sperm concentration measured across the three individuals was 3112.3 ± 964 $\times 10^6$ spermatozoa/mL, demonstrating considerable inter-individual variation. This range aligns with previously reported values for *Acipenser gueldenstaedtii*, which vary from 1.07 to 3.16 billion sperm/mL depending on reproductive conditions (Chebanov and Galich 2013).

In terms of sperm kinematic parameters, the study assessed various measures of sperm motility (Table 3). The average velocity along the actual path (VAP) was 79.66 ± 2.96 μm/s, while the straight-line velocity (VSL) was 70.87 ± 2.01 μm/s. The curvilinear velocity (VCL), reflecting the actual path traveled by the sperm, was higher at 98.58 ± 7.44 μm/s. Sperm straightness (STR) was measured at 89.26 ± 1.82%, indicating

a high degree of linearity in movement, and linearity (LIN) was 77.79 ± 4.06%. The amplitude of lateral head displacement (ALH) was 5.43 ± 0.64 µm.

Sperm motility, a critical factor for fertilization success, was measured at 58.05 ± 5.04% for total motility, while progressive motility, which indicates forward movement along a straight path, was recorded at 22.68 ± 2.23%. These values suggest that while more than half of the sperm were motile, only a small proportion demonstrated the progressive motility necessary for successful fertilization.

To minimize the influence of male gamete variability on fertilization outcomes, sperm samples collected from three males were pooled, and the same pooled sperm was used to fertilize all females. This standardized approach ensured that any observed differences in reproductive success were attributable to the females, providing a consistent and controlled baseline for evaluating female reproductive performance.

Egg quality

As shown in Table 4, egg quality parameters, including total fecundity, fecundity per kilogram of body weight, total number of eggs, number of eggs per gram, and egg diameters, were compared between the Early-Maturing (EM) and Late-Maturing (LM) groups. The LM group had an average weight of 11.4 kg, while the EM group had a lower average weight of 7.3 kg. The total fecundity was higher in the LM group (371.6 gr) compared to the EM group (184 gr); however, the fecundity per kilogram of body weight was significantly higher in the EM group ($p = 0.047$). The number of eggs per gram and egg diameters also showed significant differences between the two groups, with the EM group producing more eggs per gram (50.47 eggs/g) and smaller egg diameters compared to the LM group ($p = 0.01$ and $p = 0.019$, respectively). These findings demonstrate significant differences in fecundity per kilogram, number of eggs per gram, and egg diameters between the EM and LM groups.

Fertilization success and hatching rate

The fertilization success for the EM group was significantly higher ($p < 0.01$), with a mean of 85.09%, compared to the LM group's 50.24%. A similar pattern was observed for hatching rates, where the EM group showed a significantly higher hatching rate of 78.55% ($p < 0.01$) compared to the LM group's 40.4%.

As shown in Table 5, the EM group exhibited significantly higher fertilization success and hatching rates compared to the LM group. The EM group had a fertilization success rate of 85.09% and a hatching rate of 78.55%, while the LM group achieved only 50.24% fertilization success and 40.4% hatching rate. These results indicate that the EM group outperformed the LM group in reproductive performance, as demonstrated by the p-values (< 0.01 for both parameters), highlighting significant differences between the two groups.

Discussion

The reproductive success of sturgeon is intricately tied to the quality of both male and female gametes, with profound implications for understanding the fundamental biochemical processes governing sturgeon reproduction (Ciereszko et al. 2000). Expected disparities in reproductive performance between male and female sturgeons could stem from

Table 4 Egg Quality Parameters Based on Early-Maturing (EM) and Late-Maturing (LM) Russian Sturgeon Groups (Fecundity, Eggs Diameter)

Fish numbers	Weight (kg)	Body Length (cm)	Egg Mass (gr)	Fecundity/kg BW	Total Number of eggs	Number of Eggs/g	Eggs diameters (mm)
LM-1	11.5	128	370	941	10,810	29.22	3.57 ±0.76
LM-2	10.8	126	390	977	10,550	27.05	3.65 ±0.71
LM-3	12.0	131	355	933	11,200	31.55	3.52 ±0.69
EM-1	11.4	130	322	1591	18,149	56.36	2.76 ±0.13
EM-2	4.5	99	90	967	4350	48.33	3.11 ±0.09
EM-3	6.1	103	140	1071	6540	46.71	3.03 ±0.11
LM (Mean)	11.4	128.3	371.6	950	10,853.3	29.27	3.58
EM (Mean)	7.3	110.6	184	1210	9679.6	50.47	2.97
P-value	0.185	0.209	0.114	0.311	0.81	0.01	0.019
Significance	b	b	b	b	b	a	a

The statistical significance is indicated with the letters'a'(significant difference, $p < 0.05$) and'b'(no significant difference, $p \geq 0.05$), providing a clear understanding of the comparisons between the LM and EM groups across different parameters

Table 5 Fertilization success and hatching rate comparison between Early-Maturing (EM) and Late-Maturing (LM) Russian sturgeon Groups

Fish	Fertilization Success (%)	Hatching rate (%)
LM-1	50.16	40.25
LM-2	52.30	41.20
LM-3	48.25	39.75
EM-1	85.22	78.35
EM-2	85.10	79.50
EM-3	84.95	77.80
Mean (LM)	50.24	40.40
Mean (EM)	85.09	78.55
P-value	0.01 >	0.01 >
Significance	a	a

This table presents the fertilization success (%) and hatching rate (%) for fish from both old (LM) and young (EM) age groups. The table includes the mean values for each group, the *p*-values from statistical tests comparing the two groups, and the corresponding significance levels ('a'indicates significant differences, $p < 0.05$, while'b'indicates no significant differences, $p \geq 0.05$)

differences in their age of sexual maturity. This discrepancy notably impacts fertilization and hatching rates, particularly when comparing older and younger females.

In the Russian sturgeon (*Acipenser gueldenstaedtii*), characterized by an extended lifespan, such variability could significantly influence overall reproductive success among adult populations (Poletto et al. 2018; Waraniak et al. 2018; Zhang et al. 2020; Ulaski et al. 2022). Age has profoundly affected gamete quality and productivity, which is crucial in artificial propagation and broodstock selection.

Age-related declines in reproductive success

Our study found significant age-related declines in reproductive performance in the Russian sturgeon, particularly in fertilization success and hatching rates. Despite receiving identical hormone treatments, only two fish in the Early-Maturing (EM) group and one in the Late-Maturing (LM) group were capable of spawning. The EM group demonstrated significantly higher fertilization success (85.09%) and hatching rates (78.55%) than the LM group, which exhibited only 50.24% fertilization success and 40.4% hatching rates. These findings suggest that older females experience a decline in their capacity to produce viable eggs, in line with studies on other fish species, such as rainbow trout (Bromage et al. 1992) and common carp (Aliniya et al. 2013).

The reproductive success in sturgeons is intricately linked to gamete quality, both in males and females, as well as to the regulatory processes controlled by key hormonal pathways. Age-related differences, particularly in the context of late-maturing species such as the Russian sturgeon (*Acipenser gueldenstaedtii*), are critical in understanding the reproductive dynamics in aquaculture settings. Previous research indicates that sturgeons exhibit a prolonged and complex reproductive cycle, with females reaching sexual maturity between 6 and 10 years under aquaculture conditions (Atre et al. 2021). However, our study highlights that fish older than 20 years (Late-Maturing, LM) demonstrate

significantly lower reproductive success compared to younger fish (Early-Maturing, EM), as evidenced by reduced fertilization and hatching rates.

The hormonal regulation of reproductive processes, particularly the role of gonadotropins such as FSH and LH, plays a significant role in sturgeon reproduction. Hurvitz et al. (2005) observed that the levels of LH, in particular, are higher in sturgeons at more advanced reproductive stages, suggesting a crucial role in inducing ovulation (Hurvitz et al. 2005). This aligns with our findings, where older sturgeons exhibited diminished reproductive outcomes despite identical hormone treatments, indicating that the physiological response to these hormones may decline with age. The reduced fertilization success and hatching rates in the LM group may be attributed to a decline in the hormonal sensitivity or efficiency of gametogenesis as fish age.

Furthermore, Atre et al. (2021) elucidated the importance of the kisspeptin system in sturgeon reproductive regulation, emphasizing that kisspeptin receptors are integral to the onset of puberty and gametogenesis (Hurvitz et al. 2005). Our study aligns with this understanding, as the EM group (10 + years) demonstrated superior reproductive performance, which may be linked to optimal activation of hormonal pathways, including those modulated by kisspeptins. In contrast, the LM group's poorer performance could be indicative of diminished receptor activity or hormonal regulation efficiency in older fish.

The differences in gamete quality between the two age groups, such as larger egg diameters but lower fecundity per kilogram in the LM group, further support the notion of an age-related decline in reproductive efficiency. Previous studies have shown that while egg size often increases with age, it does not necessarily correlate with better reproductive success (Atre et al. 2021). Instead, factors such as hormone sensitivity and gamete viability may play more significant roles, as demonstrated by the lower fecundity and reproductive success in the LM group.

Gamete quality

The decline in reproductive performance with age can largely be attributed to changes in female gamete quality. Although total fecundity was higher in the LM group, the fecundity per kilogram of body weight was increased in the EM group, alongside smaller but more viable eggs. Safronov et al. (2022) found that in Russian sturgeon, older females in aquaculture systems experience increased body weight and egg size but reduced fecundity per kilogram of body weight, aligning with our findings. Moreover, our results are consistent with previous findings showing that larger females produce more eggs as they get bigger, but egg quality declines with age (Bobe and Labbé, 2010; Bromage et al. 1992).

Sperm motility and quality were controlled in this study, with all females being fertilized by a single male, ensuring that the differences observed were primarily due to the females' age-related changes. This supports the hypothesis that the decline in reproductive performance in older fish is primarily due to diminished egg quality, not sperm.

It is important to note that this study focused on basic sperm quality parameters (motility, velocity, pH, spermatocrit, and concentration), which are routinely used in aquaculture-based fertilization studies. However, more advanced assessments such as mitochondrial function, membrane integrity, and DNA fragmentation could provide deeper insights into the male reproductive status. Future studies incorporating these molecular and cellular indicators would significantly enhance our understanding of male fertility in sturgeon.

Fertilization and hatching rates

The higher fertilization and hatching rates in the EM group suggest that younger females produce eggs with better developmental potential. This observation aligns with studies on other species, where younger females often have better reproductive success due to superior gamete quality (Jokthan 2013). This finding has significant implications for sturgeon aquaculture, as hatcheries typically aim to maximize fertilization success and hatching rates to ensure efficient production. The sharp decline in reproductive performance in the LM group suggests that continuing to breed older sturgeon may result in diminishing returns.

Egg size and fecundity

Contrary to the assumption that larger eggs are always superior, our results showed that the smaller eggs from the EM group had higher fertilization and hatching success rates than the larger eggs from the LM group. This is consistent with findings in other species that egg size alone does not always correlate with higher fertilization rates (Bromage et al. 1992). Instead, factors such as post-ovulatory aging, environmental conditions, and proper husbandry practices can play significant roles in determining the success of egg fertilization and embryo development (Bobe and Labbé, 2010).

The findings of this study highlight the importance of selecting younger broodstock for sturgeon aquaculture. The sharp decline in reproductive success in sturgeon aged over 20 years suggests that such fish may not be optimal candidates for breeding. This has both biological and economic implications, as the prolonged rearing of older fish can impose unnecessary costs on hatcheries while yielding lower reproductive returns.

While this study provides clear evidence of age-related declines in reproductive performance, the underlying biological mechanisms remain unclear. Future research should explore the hormonal, genetic, and molecular factors contributing to these declines. Studies investigating oxidative stress, reproductive senescence, and changes in hormone regulation as sturgeon age could provide deeper insights into the causes of reduced gamete quality in older females. Additionally, expanding research into the optimal age range for sturgeon breeding, particularly for high-value aquaculture species like the Russian sturgeon, will help optimize production strategies.

Conclusion

This study demonstrates that early-maturing (EM) Russian sturgeon (10 + years) outperform late-maturing (LM) individuals (20 + years) in reproductive efficiency, with higher fertilization and hatching rates, as well as greater fecundity per kilogram of body weight. The decline in reproductive performance in LM sturgeon is linked to age-related reductions in gamete quality and hormonal responsiveness. These results suggest that the prolonged rearing of older sturgeon in aquaculture settings may not be economically or biologically justified, as it leads to diminished reproductive returns and increased operational costs. Moreover, early-maturing sturgeon are more suitable for aquaculture breeding programs, offering improved reproductive success and being economically viable. Furthermore, these findings contribute to the broader understanding of age-related

reproductive dynamics in late-maturing species, offering valuable insights for managing other endangered or commercially important fish species.

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Author contribution Gokhan Tuncelli and Momin Momin conducted the formal analysis, investigation, and data curation. Gokhan Tuncelli and Momin Momin drafted the original manuscript, contributed to visualization, and reviewed and edited the manuscript. Devrim Memis contributed to the conceptualization, methodology, validation, and resources, and was responsible for project administration. All authors reviewed and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval The present experiments were carried out according to the legislation on the use of aquatic animals for experimental and other scientific purposes in Turkey with approval of Istanbul University, Animal Experiments Local Ethics Committee (Number: 2022/18).

Competing interests The authors declare no competing interests.

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References

Aliniya M, Khara H, Noveiri SB, Dadras H (2013) Influence of age of common carp (Cyprinus carpio) broodstock on reproductive traits and fertilization. Turk J Fish Aquat Sci 13:19–25. https://doi.org/10.4194/1303-2712-v13_1_03

Atre I, Mizrahi N, Hausken K, Yom-Din S, Hurvitz A, Degani G, Levavi-Sivan B (2021) Molecular characterization of kisspeptin receptors and gene expression analysis during oogenesis in the Russian sturgeon (*Acipenser gueldenstaedtii*). Gen Comp Endocrinol 302:113691. https://doi.org/10.1016/j.ygcen.2020.113691

Bobe J, Labbé C (2010) Egg and sperm quality in fish. Gen Comp Endocrinol 165(3):535–548. https://doi.org/10.1016/j.ygcen.2009.02.011

Bromage N, Jones J, Randall C, Thrush M, Davies B, Springate J, Duston J, Barker G (1992) Broodstock management fecundity egg quality and the timing of egg production in the rainbow trout (*Oncorhynchus mykiss*). Aquaculture 100(1–3):141–166. https://doi.org/10.1016/0044-8486(92)90355-O

Bronzi P, Rosenthal H (2014) Present and future sturgeon and caviar production and marketing: a global market overview. J Appl Ichthyol 30(6):1536–1546. https://doi.org/10.1111/jai.12628

Chebanov, M.S. 1996. Sturgeons in aquaculture: prospects of resource saving technologies. Abstract of resource saving technologies in aquaculture, Krasnodar. pp. 102–103.

Chebanov, M. S., & Galich, E. V. (2013). Sturgeon hatchery manual. FAO fisheries and aquaculture technical paper, No. 558, Ankara FAO, 330.

Chen X, Liu B, Lin D (2022) Sexual maturation, reproductive habits, and fecundity of fish. In: Chen X, Liu B (eds) Biology of Fishery Resources. Springer, Singapore. https://doi.org/10.1007/978-981-16-6948-4_5

Ciereszko A, Ottobre JS, Glogowski J (2000) Effects of season and breed on sperm acrosin activity and semen quality of boars. Anim Reprod Sci 64(1–2):89–96. https://doi.org/10.1016/S0378-4320(00)00194-9

Hurvitz A, Degani G, Goldberg D, Din SY, Jackson K, Levavi-Sivan B (2005) Cloning of FSHβ, LHβ, and glycoprotein α subunits from the Russian sturgeon (*Acipenser gueldenstaedtii*), β-subunit mRNA expression, gonad development, and steroid levels in immature fish. Gen Comp Endocrinol 140(1):61–73. https://doi.org/10.1016/j.ygcen.2004.09.019

Jokthan GE (2013) Effect of age of spawned catfish (*Clarias gariepinus*) broodstock on quantity of eggs and milt produced and growth performance of fry. IOSR J Agri Vet Sci 5(3):59–61. https://www.iosrjournals.org/iosr-javs/papers/vol5-issue3/L0535961.pdf

NOAA Fisheries (2024) Atlantic sturgeon: species profile. National Oceanic and Atmospheric Administration. https://www.fisheries.noaa.gov/species/atlantic-sturgeon

Poletto JB, Cocherell DE, Baird SE, Nguyen TX, Cabrera-Stagno V, Farrell AP, Fangue NA (2018) Age and sex-related differences in the physiological stress response in wild largemouth bass. J Fish Biol 92(3):800–815. https://doi.org/10.1111/jfb.13805

Safronov AS, Mugue NS, Barmintseva AE, Shcherbakova VD, Sukhover KV (2022) Comparison of fish breeding characteristics and survival rate of offspring of domesticated and grown "from eggs" Russian sturgeon *Acipenser gueldenstaedtii* (Acipenseridae) females, at artificial reproduction. J Ichthyol 62(7):1466–1475. https://doi.org/10.1134/S0032945222060261

Ulaski ME, Blackburn SE, Jackson ZJ, Quist MC (2022) Management goals for conserving white sturgeon in the Sacramento-San Joaquin river basin. J Wildl Manag 13(2):334–343. https://doi.org/10.3996/JFWM-21-070

Van Eenennaam JP, Doroshov SI, Moberg GP, Watson JG, Moore DS, Linares J (1996) Reproductive conditions of the Atlantic Sturgeon (*Acipenser oxyrinchus*) in the Hudson. River Estuaries 19(4):769. https://doi.org/10.2307/1352296

Waraniak JM, Forsythe PS, Scribner KT, Baker EA (2018) Molecular diet analysis reveals predator–prey community dynamics and environmental factors affecting predation of larval lake sturgeon (*Acipenser fulvescens*). J Fish Biol 93(3):386–397. https://doi.org/10.1111/jfb.13726

Williot P, Sabeau L, Gessner J, Arlati G, Bronzi P, Gulyas T, Berni P (2001) Sturgeon farming in Western Europe: recent developments and perspectives. Aquat Living Resour 14(6):367–374

Zhang F.-T, Shen Z-Y, Yu D, Gao X, Liu H-Z (2020) Genetic diversity and reproductive success of a wild population of Chinese sturgeon (Acipenser sinensis) from the Yangtze River inferred from juveniles born in 2014. Zoological Research 41(4):423–430. https://doi.org/10.24272/j.issn.2095-8137.2020.011

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