



From adults to offspring: Wi-Fi RF-EMR exposure in adult zebrafish impairs reproduction and transgenerationally effects development and behavior of progeny

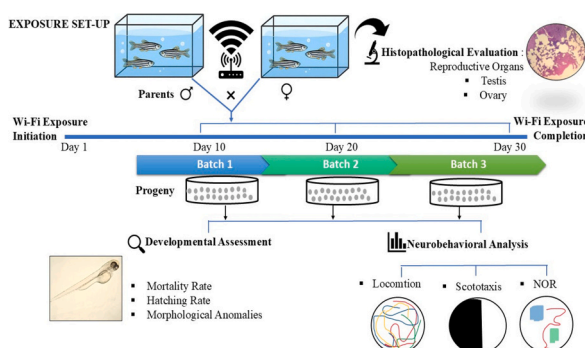
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HIGHLIGHTS

- Zebrafish were exposed to 4G Wi-Fi RF-EMR for 30 days, 4 h/day.
- Fish were bred on 10th, 20th, and 30th day of exposure.
- Exposure caused damage to gonadal histoarchitecture in both males and females.
- The progeny of exposed adults showed severe developmental malformations and neurobehavioral alterations.
- Study highlights progressive transgenerational effects of Wi-Fi RF-EMR that intensify with longer exposure.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:

Developmental toxicity
Neurobehavior
Transgenerational effects
Reproductive health
Wi-Fi
RF-EMR
Follicular atresia

ABSTRACT

The widespread presence of wireless communication technologies in modern human society is raising concerns about the biological effects of radiofrequency electromagnetic radiation (RF-EMR). In this study the impacts of Wi-Fi induced RF-EMR exposure in *Danio rerio* (zebrafish) were examined. Adult zebrafish were exposed to 4 h of RF-EMR daily from a 4G Wi-Fi router over a 30-day period. The exposed adult fish were bred under exposure free condition, on the 10th, 20th and 30th day of experiment. Fertilized embryos obtained from these breeding events were maintained under EMF-free conditions and were observed up to 10 dpf and analysed for developmental and neurobehavioral changes. After completion of the exposure on the 30th day, the adult male and female gonads were processed for histomorphological study. Histopathological analysis revealed significant testicular abnormalities, including seminiferous tubule disintegration, reduced spermatids, and abnormal lumina. Ovaries showed notable follicular degeneration and stromal disruption. Significant rates of mortality and gross morphological abnormalities like yolk sac edema, pericardial edema, curved axis and tail deformities were found in the progeny of exposed fish. Malformation rates increased significantly with longer adult exposure periods. Neurobehavioral tests on these larvae at 10 dpf showed anxiety-like behavior. The results indicated progressive

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<https://doi.org/10.1016/j.scitotenv.2025.180982>

Received 22 August 2025; Received in revised form 14 November 2025; Accepted 14 November 2025

Available online 19 November 2025

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decline in reproductive health of adults and increased adversities in the progeny. The study highlights long-term biological risks of widespread electromagnetic radiation exposure and calls for further research into potential transgenerational effects.

1. Introduction

The escalating deployment of wireless communication technologies has resulted in widespread anthropogenic exposure to non-ionizing electromagnetic fields (EMF), predominantly radiofrequency electromagnetic radiation (RF-EMR). Sources of RF-EMR like mobile phones, Wi-Fi routers and cellular base stations are now integral components of contemporary society. The extensive adoption of wireless fidelity (Wi-Fi) technology has profoundly reshaped modern life, providing ubiquitous internet access. These Wireless Local Area Networks (WLAN) primarily operate around 2.45 GHz, contributing to an increasing presence of radiofrequency electromagnetic radiation (RF-EMR) in our environment. Despite the convenience these devices offer, their extensive use has sparked significant scientific investigation and public concern regarding potential biological and health impacts. This concern is further amplified by the International Agency for Research on Cancer's (IARC) classification of radiofrequencies as 2B agents, meaning they are "possibly carcinogenic to humans."

Research into the biological effects of RF-EMR, particularly from Wi-Fi, presents a complex and often contradictory picture, making definitive conclusions challenging. Despite these complexities, a common finding across several studies is oxidative stress, which has been reported as a significant effect in Wi-Fi-induced biological changes. Radiation-induced oxidative stress is consistently reported in both mammalian and non-mammalian systems. In rodents exposed to RF-EMF (900 MHz–2.45 GHz), elevated reactive oxygen species (ROS), increased lipid peroxidation (MDA), and decreased antioxidant enzymes (SOD, CAT, GPx) have been observed in the brain, testes, and liver, sometimes accompanied by DNA damage and partial recovery after prolonged exposure (Panagopoulos et al., 2021), indicating that mammals demonstrate adaptive and repair potential. Similar oxidative responses occur in fish, amphibians, and insects, but these species particularly at early developmental stages exhibit weaker antioxidant defences and limited repair capacity (Meyer et al., 2024). In aquatic models, the conductive water medium can enhance EMF absorption, potentially amplifying oxidative effects.

Various other studies have explored neurological, reproductive, and cardiovascular effects of Wi-Fi exposure. Neurological investigations have revealed a spectrum of impacts. Mohamed et al. (2022) reported degeneration of hippocampal pyramidal and granular neurons and increased neurofibrillary tangles in rats exposed to Wi-Fi. Othman et al. (2017b) conducted multiple studies showing various neurological effects: in-utero Wi-Fi exposure impaired neurodevelopment and effected cholinesterase activity in rat offspring aged 1–17 days. Early-life exposure adversely affected physical and neurodevelopment, as well as emotional, motor, and exploratory behaviors in adulthood. These effects were accompanied by disruptions in brain oxidative balance and serum biochemistry, with outcomes often being gender dependent. A separate study also found that Wi-Fi exposure induced anxiety-like behavior and increased acetylcholinesterase activity in the brains of male rats (Othman et al., 2017a). On the other hand, Hosseini et al. (2019) found no significant differences in reaction time, short-term memory, or reasoning ability in human participants following two-hour Wi-Fi exposure sessions. Also, Wu et al. (2023) found no change in neurobehavior of offspring or antioxidant enzyme activities, after prenatal and early-life Wi-Fi exposure in rats.

Studies on reproductive function indicated potential concerns, though findings have been inconsistent. Dasdag et al. (2015) observed that long-term exposure to 2.4 GHz RF emitted from Wi-Fi equipment affected reproductive parameters in male rats, including increased head

defects in sperm, decreased weight of the epididymis and seminal vesicles and reduction in diameter of seminiferous tubules and thickness of tunica albuginea. Shokri et al. (2015) further investigated that 7-h exposure to 2.45 GHz Wi-Fi radiation in Wistar rats decreased sperm parameters and seminal vesicle weight, increasing apoptosis in seminiferous tubules. However, Laudisi et al. (2012) found no harmful effects on fertility or development in animals following prenatal exposure to non-thermal SAR levels. Similarly, Sambucci et al. (2010) reported that prenatal exposure to Wi-Fi signals had no adverse effects on pregnancy outcomes, peripheral B-cell compartment, or antibody production in mice. Sambucci et al. (2011) further investigated early postnatal life exposure to Wi-Fi, and found no detrimental effects on the developing immune system, except for a reduced IFN- γ production in male mice spleen cells exposed to the highest SAR level. Poullietier de Gannes et al. (2012, 2013) also found no effects on the reproduction and pre/post-natal development of rats exposed to Wi-Fi signals, even at SAR levels up to 4 W/kg. Also, in a systematic review conducted by Dongus et al. (2022), it was concluded that Wi-Fi exposure below regulatory limits does not cause any significant health effects. They also noted that sporadic findings were not consistent in terms of outcomes or exposure-response associations, and that studies with higher quality criteria were less likely to report effects.

Cardiovascular effects have also been explored. Saili et al. (2015) demonstrated that acute Wi-Fi exposure (2.45 GHz) increased heart rate and arterial blood pressure in male rabbits. Montzeri et al. (2019) investigated Wi-Fi's effects on rats with induced stroke, finding that exposure to Wi-Fi waves significantly increased Troponin I levels, a diagnostic marker for heart attack, suggesting an increased risk.

Given the ongoing scientific debate and the recognized sensitivity of developing organisms, models like zebrafish (*Danio rerio*) are valuable for studying developmental and neurobehavioral impacts of environmental stressors. Though not completely alike, the striking similarity of the presence of aquatic environment during the embryonic development in zebrafish as well as in human and other amniotes, makes zebrafish a physiologically relevant model to understand reproductive and development related studies. Despite the quantitative ionic differences in the amniotic fluid and naturally occurring freshwater environments, the highly conserved developmental pathways of vertebrate development, make zebrafish a valid model for assessing EMF-induced developmental and germ-cell effects and extrapolate the same to human health.

While previous studies have examined various durations and intensities of Wi-Fi exposure, a comprehensive understanding of transgenerational and long-term developmental impacts, particularly from parental exposure, remains a critical research gap. Therefore, the following experimental design was developed to assess the effects of EMF exposure on the reproductive system of adult zebrafish and on developmental and behavioral outcomes in their progeny.

2. Methods and material

2.1. Zebrafish housing and maintenance

Adult wild-type *Danio rerio* were procured from a registered supplier and acclimated under standardized laboratory conditions. Fish were maintained in filtered, aerated aquatic systems to optimize dissolved oxygen levels. Water pH was maintained at neutral level (7.0) to resemble natural freshwater conditions. Temperature was regulated within a range of 25–28°C to support optimal reproductive behavior and embryonic development. Relative humidity was controlled at 40–45%. A 14:10 h light-dark photoperiod was established to simulate natural

cycles. Fish received a commercial pelleted diet thrice daily, with detritus and uneaten food promptly removed via glass pipette to prevent water contamination.

2.2. RF-EMR exposure protocol

Adult zebrafish were exposed to RF-EMR generated by a Wi-Fi router, CP Plus, Model: CP-XR-DE41-S, operating at 2.4 GHz (Wi-Fi 802.11 b/g/n) with a 20 MHz channel bandwidth; for 4 h daily over a 30-day period. The duty cycle was determined to be 81.4 %, based on experimentally measured WLAN duty cycles during continuous 1080p video streaming (e.g., YouTube) at a 6 Mbps PHY data rate (reported average $\approx$ 81.39 %). The experimental setup consisted of two separate fish tanks (30x18x23cm), in which 20 male and 20 female fishes were housed separately. The router was positioned centrally between both the experimental tanks at a distance of 0.2 m from each. An electromagnetic radiation detector (Smiledrive ET825, Version: 9024-EN-00) was used to measure radiation intensity at multiple points. The electric field strength (E) was recorded at two vertical depths i.e. surface and bottom of the tank water and across three equidistant lateral columns along the tank's length. The far field power density under the current exposure conditions was calculated based on the transmitted power, antenna gain, and distance at distinct points as mentioned above. The power density (P_D) at each point was determined using the plane-wave relation:

$$P_D = \frac{P_o G_{tx}}{4 \pi D^2}$$

Where: $P_D = W/m^2$; P_o = output W from antenna; G_{tx} = antenna gain; D = distance from the antenna in meters (Dasgupta et al., 2020). The minimum and maximum calculated power densities on the side closest (0.2 m) and farthest (0.38 m) to the router were $1.9 W/m^2$ and $6.8 W/m^2$ approximately.

The specific absorption rate (SAR) was calculated using the following formula:

$$SAR = \frac{\sigma E^2}{m_d}$$

Where σ = conductivity of material (for zebrafish tissue taken as $1 S/m$); E = electric field in V/m , m_d = the mass density ($1000 Kg/m^3$). Range of SAR recorded was 0.716 to $2.59 W/Kg$ for a minimum to maximum electrical field measurements within the water tank. The water temperature in both experimental tanks was monitored at regular intervals in various columns of the tank water using mercury thermometers fixed at all four corners of the tank. The temperature remained constant at $28^\circ C$ and no notable temperature variation was observed during the exposure period, confirming the absence of measurable thermal effects within the tanks.

In the present study, a separate RF-EMR free control environment was maintained to isolate exposure-related effects. Preliminary measurements indicated negligible thermal, vibrational, or mechanical effects from the exposure apparatus when the transmitter was powered but radio transmission disabled. The temperature stability and absence of physical disturbances were verified throughout the experimental period. Therefore, the possibility of non-EMF confounding factors was considered minimal, based on our current observations and also a few other earlier published studies (Khira and Ugini, 2024; de Gannes et al., 2013).

2.3. Breeding and egg procurement

The breeding procedure was carried out in the absence of the RF-EMR exposure. 20 adult male and female fish were housed in two different tanks (for controlled breeding). After every 10 days of exposure, three breeding stocks were randomly selected in 3:2 ratio (female:

male) from the adult tanks and introduced into the breeding chambers. The randomised selection was followed so as to avoid repeated use of the same individuals and potential genetic or health-related bias. Immediately after the breeding was accomplished, the fertilized eggs were collected in a Petri dish, and rinsed three times with embryo medium. This process was repeated two more times at 10-day intervals, resulting in a total of three breeding events over the 30-day exposure period. The resultant batch of fertilized eggs of each breeding event were labelled as B1, B2 and B3 (obtained after 10th, 20th and 30th day of exposure respectively). The experiment was independently replicated three times to ensure statistical robustness, and data from all runs were pooled for analysis. In the statistical models, clutch or tank was included as a random effect to account for genetic and environmental similarities within families, thereby isolating the true effects of RF-EMR exposure with greater reliability.

2.4. Histological analysis (Adults)

To investigate the effects of sub-chronic EMF exposure on adult zebrafish, histomorphological analysis of testes and ovaries of the control and exposed adult fish was performed using Hematoxylin and Eosin (H&E) staining method as per Slaoui and Fiette (2010). Tissues were fixed, sectioned, stained, and observed under a microscope to assess cellular morphology and tissue architecture. For each fish ($n = 4$ per group), three serial sections were analysed, and five non-overlapping microscopic fields were randomly selected per section. All slide readings and quantitative assessments were conducted under blinded conditions to minimize observer bias. Germ cell staging and gonadal maturation were identified according to the criteria of Maack and Segner (2003).

In ovaries, atretic follicles were identified based on characteristic morphological features, and the proportion of each follicular stage was calculated relative to the total follicle count. Testicular analysis involved quantification of spermatogonia, spermatocytes, spermatids and spermatozoa as representative germ cell stages using the Cell Counter plugin in Fiji (ImageJ software). Image acquisition and measurement were performed using Catymage software (Catcam E series, Catalyst Biotech, India). Data were expressed as mean $\pm$ SEM from three serial sections per fish ($n = 4$ per group) and represented as percentage cell count for comparative statistical analysis between control and exposed groups.

2.5. Embryo screening

The following parameters were assessed in the progeny of the EMR exposed adults:

2.5.1. Hatching rate

The eggs collected from both experimental and control groups were continuously monitored for hatchability. The number of hatched larvae was counted daily and expressed as a percentage of the total initial egg count.

2.5.2. Mortality rate

Post fertilization, embryos were monitored daily up to 10 dpf. Embryos were scored as 'dead' if the appearance of the egg changed from transparent to opaque under a compound microscope or no locomotor activity was observed in the larvae.

2.5.3. Morphological observation

The offspring were meticulously screened for any morphological anomalies or developmental defects, including deformities of the body axis, fins, spine, and ocular structures. The incidence of identified deformities was recorded, and their longitudinal rate of occurrence in B1, B2 and B3 was calculated and analysed.

2.6. Neurobehavioral analysis

Analysis of neurobehavioral patterns was conducted to assess stress, anxiety, and cognitive functions in the offspring. Behavioral parameters were recorded using a handycam (Sony 9.2MP) and the videos were analysed subsequently.

2.6.1. Locomotion analysis

Locomotion patterns were evaluated as indicators of coordinated muscle development and functional neuromuscular connectivity. Ten larvae from each group were individually transferred to Petri dishes, and their movement was recorded for a set period of 10 min using video tracking. The total distance moved and the swimming speed were quantitatively analysed as indicators of locomotor behavior with the help of ToxTrac video tracking application (version 2.91). The readings were then used to interpret the behavior type i.e., normal or stress/anxiety.

2.6.2. Scototaxis behavior (light-dark preference test)

The light-dark preference assay was performed to investigate phototactic preference, following the method of Bai et al. (2016). For this assay, one half of the Petri dish was covered with black paper from below and the outer walls, while the other half with a white paper, thereby creating distinct dark and light zones. Six larvae from each batch were introduced into these dishes and their movement and the time spent in each zone were recorded for 6 min. Scototactic preference, defined as the tendency to spend more time in the dark zone, was considered an indicator of stress. The preference for light or dark was quantified based on the proportion of time spent in each zone.

2.6.3. Novel object recognition test

The procedure involved placing six larvae in a Petri dish and recording their behavior for 3 min. A novel object (a pebble) was introduced at 30 s, and a second novel object at 90 s. We quantified the larvae's exploratory behavior and time spent near each object at three time points: T1 (30 s), T2 (60 s), and T3 (90 s). The Preference Index (PI) was calculated to determine recognition memory, with a value greater

than 0.5 indicating a preference for the novel object and a value less than 0.5 suggesting impaired cognition.

2.7. Statistical analysis

Statistical analysis was performed using GraphPad Prism (version 9.3.1). Quantitative histomorphology was analysed using student's *t*-test to compare control and exposed fish. For mortality and hatching rates, binary responses were computed. In order to determine whether RF-EMR exposure exerts significant effects on the development, stress, and behavior of progeny of exposed adults relative to the control group, as well as to assess whether extended exposure duration in the parental groups influences these parameters in their progeny, the results were subjected to two-way ANOVA followed by Tukey's post hoc multiple comparison test. A significance threshold of $p < 0.05$ and a 95 % confidence interval were applied.

3. Results

3.1. Histological analysis (adults)

3.1.1. Qualitative analysis

The ovaries of control females showed normal developmental patterns of oocytes and no visible defects were observed (Fig. 1A to 1D). However, in exposed adult female, the ovaries consistently demonstrated atresia of mature oocytes, atretic follicles, various degrees of disintegration, oviduct filled with egg debris, fusion of vitellogenin granules to intracellular mass, indicating a compromised reproductive capacity in the parent generation due to prolonged RF-EMR exposure (Fig. 1E to 1H). The control male fish showed normal tissue architecture in the testes (Fig. 2A and B). The exposed male fish exhibited disintegration of seminiferous tubules, disruption of stromal and luminal architecture, indicating the direct impairment of the process of spermatogenesis. In addition, clusters of vacuolated cells and apoptotic cells were observed (Fig. 2C to 2F).

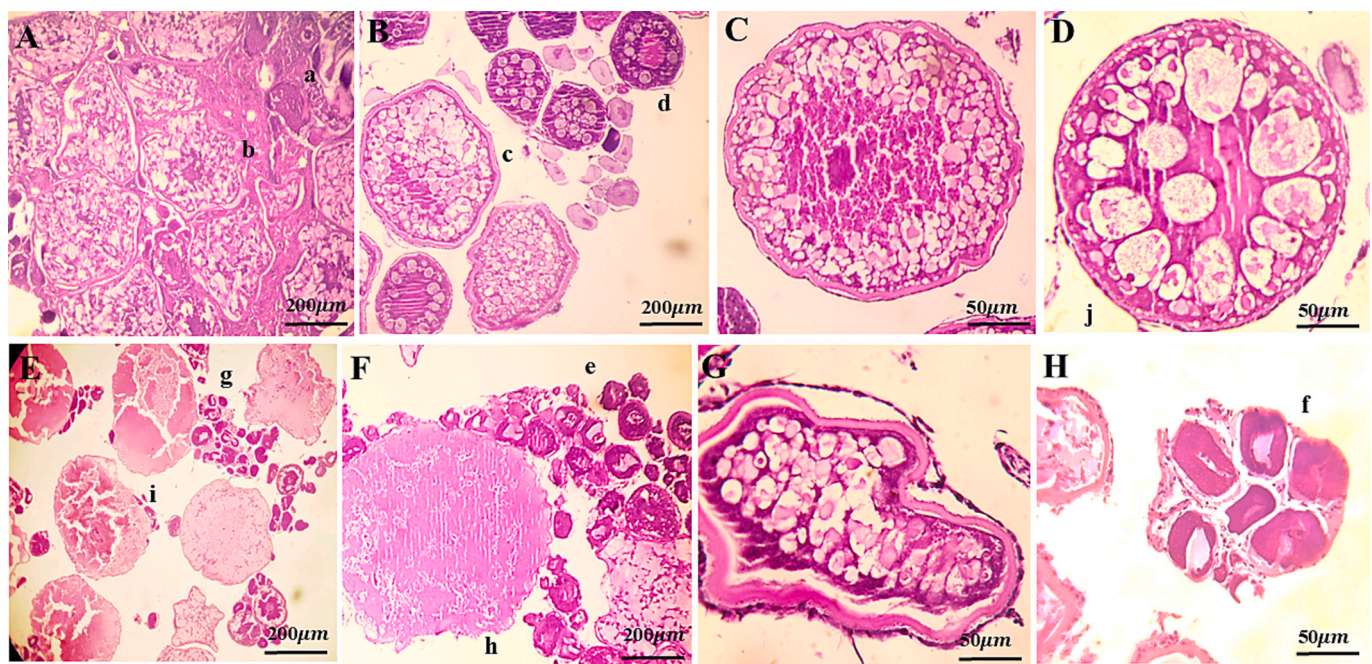


Fig. 1. Histological analysis of zebrafish ovary of control (A to D); exposed (E to H). a) Meiotic oogonia, b) stage 1 oocytes, c) stage 2 oocytes, d) stage 3 oocytes, e) atresia of mature oocytes, f) atretic follicles, g) various degrees of disintegration, h) oviduct filled with egg debris, i) fusion of vitellogenin granules to intracellular mass, j) follicle cells; ($n = 4$).

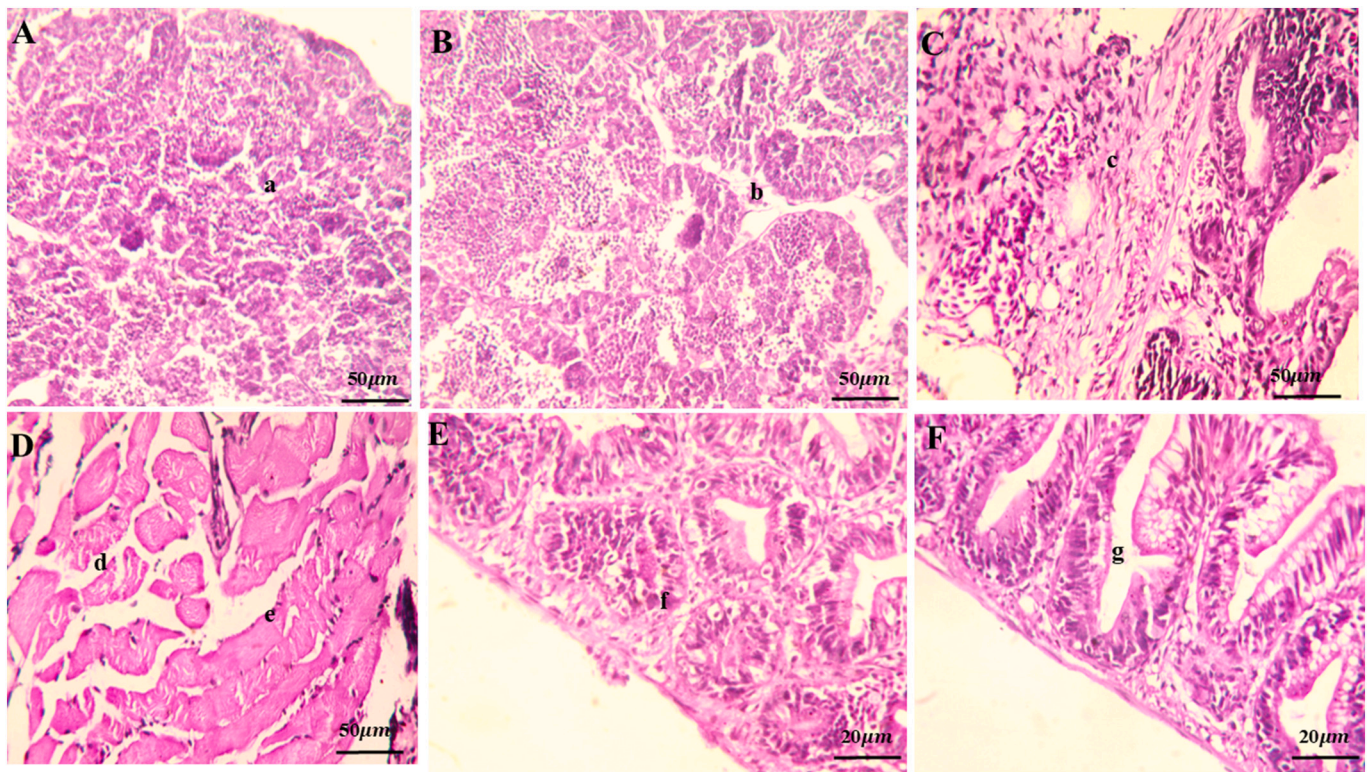


Fig. 2. Histological analysis of zebrafish testes of control (A and B) and treated (C to F). a) spermatocytes, b) spermatocyst, c) reduced number of spermatids, d) seminiferous tubules disintegration, e) abnormal lumina, f) apoptotic cells, g) cluster of vacuolated cells; (n = 4).

3.1.2. Quantitative analysis

Five distinct developmental stages of ovarian follicles were observed: (I) primary growth, (II) cortical alveolar, (III) early vitellogenic, (IV) late vitellogenic, and (V) mature stage (Fig. 3A). Stage-wise quantification of follicular atresia revealed a significant increase in the proportion of atretic follicles at the primary growth stage in the exposed group compared to the control ($***p < 0.001$; Fig. 3B). Similarly, distinct testicular germ cell stages were identified in testes, including spermatogonia, spermatocytes, spermatids, and spermatozoa (Fig. 3C). Quantitative analysis demonstrated a statistically significant reduction in the number of spermatogonia ($*p = 0.031$) and spermatozoa ($**p = 0.004$) in EMF-exposed fish relative to control fish (Fig. 3D).

3.2. Embryo screening

3.2.1. Mortality rate

Day wise mortality rate was observed up to 10 dpf in the control as well as B1, B2 and B3 batches. The progeny of exposed fish consistently revealed significantly higher mortality rates across all experimental batches i.e. B1, B2 and B3 compared to their respective control groups. The increase in embryo mortality was directly proportional to the duration of parental RF-EMR exposure (Fig. 4A, B and C). In other words, longer exposure of the adult fish to RF-EMR resulted in a progressively higher rate of embryo mortality, suggesting a strong influence of parental exposure duration on offspring survival.

3.2.2. Hatching rate

Hatching rates for B1 and B2 (Fig. 5A and B) showed no statistically significant difference relative to the control groups, although a slight delay was noted. However, B3 (Fig. 5C) exhibited a significant delay ($*p = 0.012$) in hatching. This suggests that parental RF-EMR exposure has a progressive influence on embryonic hatching success, with longer exposure periods leading to more pronounced developmental delays.

3.2.3. Developmental abnormalities

Morphological observation of the control embryos showed normal pattern of development. Parental exposure to RF-EMR caused a significant duration dependent increase in developmental deformities in embryos compared to the control group. Significant number of larvae across all batches i.e. B1, B2 and B3, revealed several morphological anomalies i.e. tail kink, pericardial edema, yolk sac edema, bent spine (scoliosis and lordosis) and stunted growth (Fig. 6B to 6H). Larvae from Batch 1 (10-day parental exposure) exhibited only tail malformations. Notably, the incidence of tail deformities showed a progressive increase across batches derived from parents with longer EMF exposure durations. The pericardial edema and yolk sac edema were found only in B2 and B3, wherein the later showed highly significant incidence of the same. This indicates that both the incidence and diversity of morphological malformations were notably greater in larvae from parents exposed for the full 30-day period (B3), suggesting a time-dependent increase in susceptibility to developmental defects with prolonged parental exposure. (Fig. 7)

3.3. Neurobehavioral outcomes in offspring

3.3.1. Locomotion

Larvae derived from all RF-EMR-exposed parental groups exhibited a significant reduction in both total distance travelled (Fig. 8A) and mean swimming velocity (Fig. 8B) relative to controls. Two-way ANOVA revealed that these locomotor impairments were influenced by parental exposure duration, with progressive decreases observed from B1 to B3. These findings indicate that prolonged parental Wi-Fi exposure elicits a dose-dependent exacerbation of locomotor deficits in the offspring, likely reflecting heightened stress and reduced activity levels.

3.3.2. Scototaxis behavior

In the scototaxis test, larvae from all three batches (B1, B2, and B3) spent significantly more time in the dark zone compared to the control

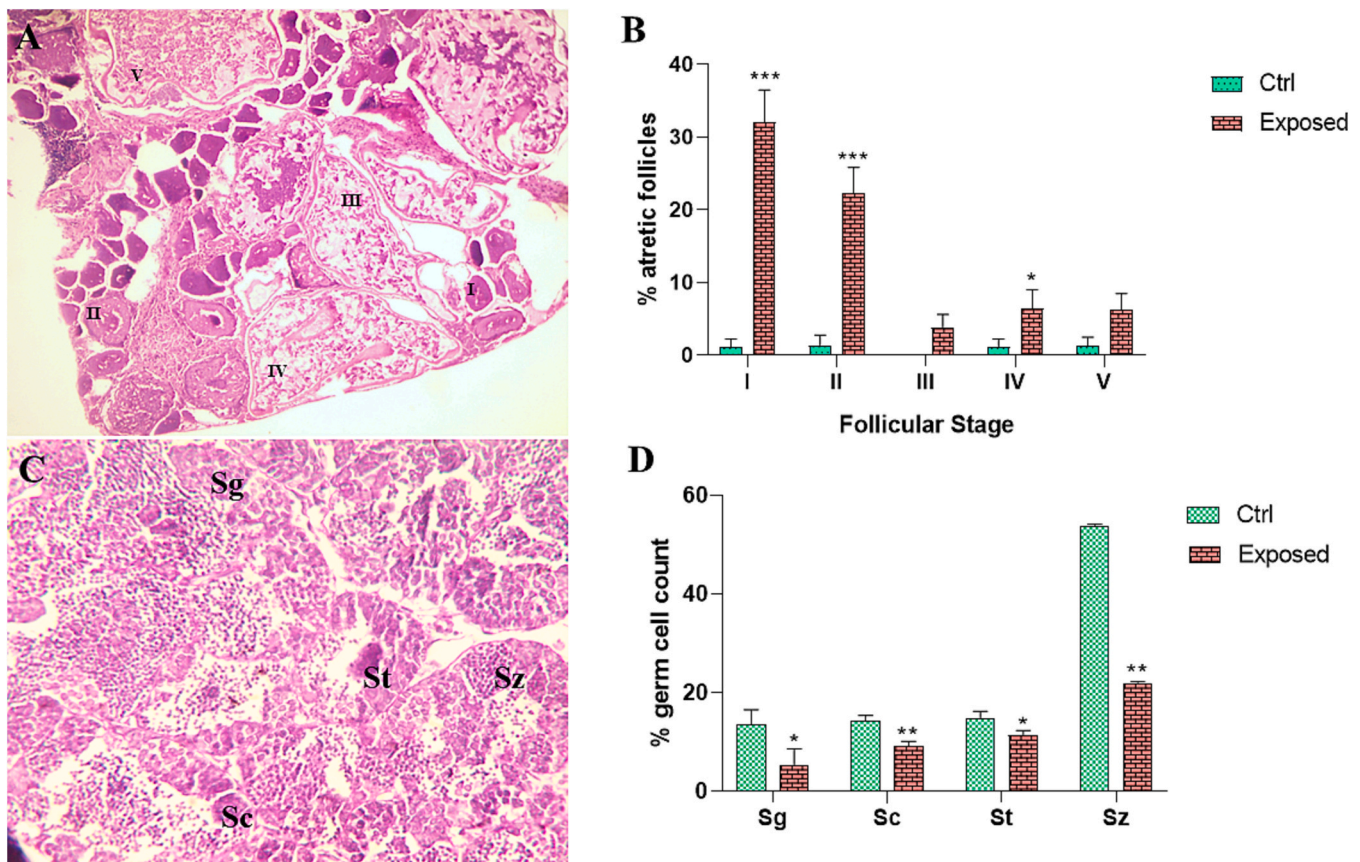


Fig. 3. Morphological analysis of zebrafish (Ctrl and exposed) follicular (A and B) and testicular structures (C and D). A) Ovarian follicular staging. I- Primary growth stage, II- cortical alveolar stage, III- early vitellogenic stage, IV- Late vitellogenic stage, V- mature stage. B) % atretic follicles observed in each stage represented as control vs exposed. * $p = 0.08$, *** $p < 0.001$. C) Identification of different germ cell types in testicular section. sg- spermatogonia, sz- spermatozoa, sc- spermatocytes, st- spermatids. D) % cell count of different germ cells represented as control vs exposed. Sg- * $p = 0.043$, Sc- ** $p = 0.003$, St- * $p = 0.032$, Sz- ** $p = 0.004$. Results are representative of four animals/group analysed separately and expressed in percentage as mean $\pm$ SEM. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; (n = 4).

group. A two-way ANOVA further indicated that the time spent in the dark zone increased progressively across the batches, with B3 showing the highest duration. This suggests that longer parental exposure to Wi-Fi leads to a time-dependent increase in stress and anxiety-like behavior in the offspring (Fig. 9A and B).

3.3.3. Novel object recognition

In the control group, the Preference Index (PI) values consistently remained above 0.5 across all time points, indicating intact cognitive ability and a natural tendency to explore novel stimuli. In contrast, the progeny of EMF-exposed parents exhibited PI values below 0.5, suggesting compromised cognitive performance and impaired recognition memory. This decrease in exploration was most pronounced in the larvae of B3, whose parents had the longest exposure (30 days), indicating a depression-like state (Fig. 10).

4. Discussion

The unprecedented proliferation of wireless communication technologies has been paralleled by increased human exposure to radio-frequency electromagnetic radiation (RF-EMR), raising significant concerns about its potential biological effects. This study evaluates the transgenerational impacts of Wi-Fi-induced RF-EMR exposure on *Danio rerio* (zebrafish), focusing on adult reproductive integrity and subsequent effects on the developmental and neurobehavioral phenotypes in the offspring.

The adverse effects of electromagnetic field exposure on biological systems, particularly the reproductive system, have been reported

earlier in both vertebrate and invertebrate models. Long-term exposure to electromagnetic fields has been shown to change gonadal architecture, interfere with hormone regulation, and reduce fertility (Asghari et al., 2016). In the present study, exposure of adult female zebrafish to RF-EMR induced distinct histological alterations in ovarian architecture, marked by increased follicular atresia, disrupted stromal architecture and a decline in healthy oocytes across developmental stages. Quantitative analysis revealed a significant elevation in atretic follicles, particularly at the primary growth stage, suggesting premature follicular degeneration and disrupted oogenesis. Such changes indicate that Wi-Fi radiation may impair follicular maturation and reduce overall ovarian functional integrity. Although direct studies in zebrafish ovaries are limited, similar EMR-induced ovarian degeneration has been reported in rodents and other aquatic species, where prolonged exposure caused oxidative stress, vascular congestion, and increased atresia. These effects align with the view that RF-EMR enhances reactive oxygen species (ROS) generation, leading to lipid peroxidation, mitochondrial damage, and apoptosis in developing oocytes. Parallel findings in mammalian gonads such as vacuolation and germ cell loss (Shokri et al., 2015; Dasdag et al., 2015) indicate the role of oxidative stress as a central mechanism in EMR-induced ovarian damage. Our results also align with previous findings by Burcu et al. (2020), who reported structural changes in the ovarian tissues of rats exposed to EMF both during pregnancy and after delivery. Similarly, RF-EMR exposure has been reported to disrupt ovarian folliculogenesis, alter hormonal regulation, and reduced fertility in female rats (Saygin et al., 2018; Alchalabi et al., 2016). In another study, increased oxidative stress and markers of cellular apoptosis (caspase-3) were observed in ovarian tissues following

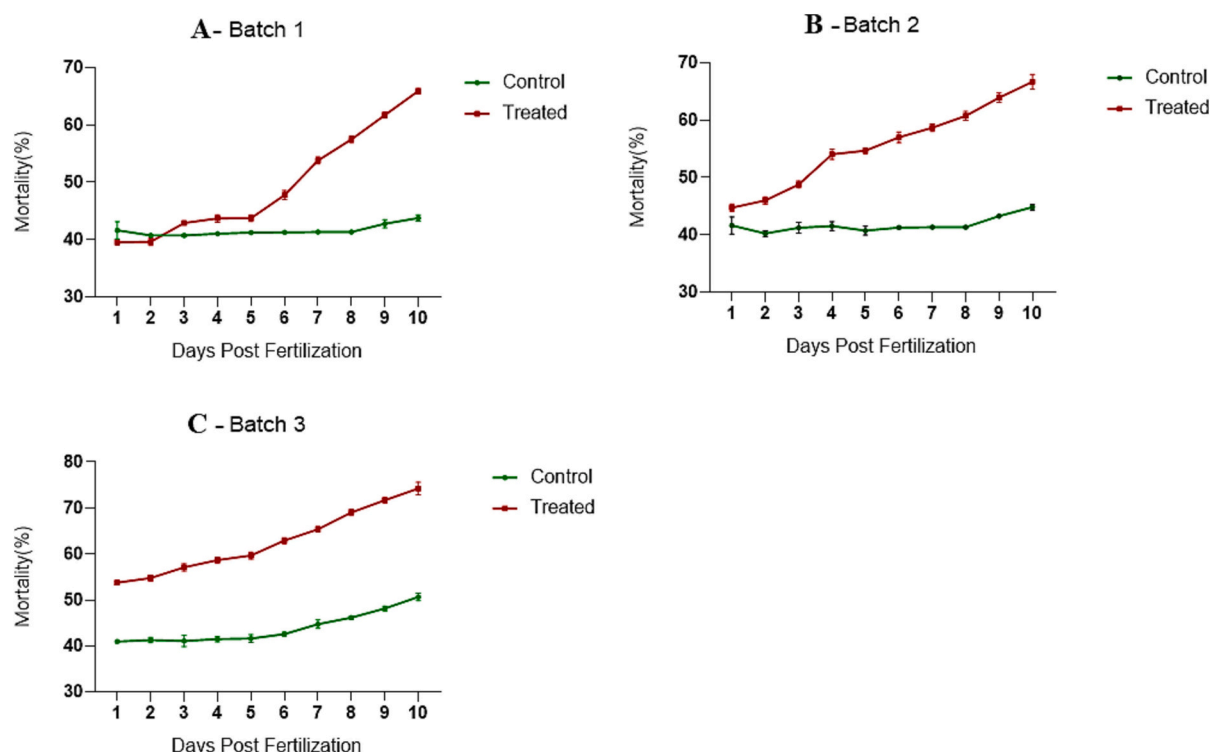


Fig. 4. Comparative analysis of mortality (%) in progeny of control and exposed fish bred on 10th (A- Batch 1), 20th (B- Batch 2) and 30th (C- Batch 3) day of exposure; ($n = 100$).

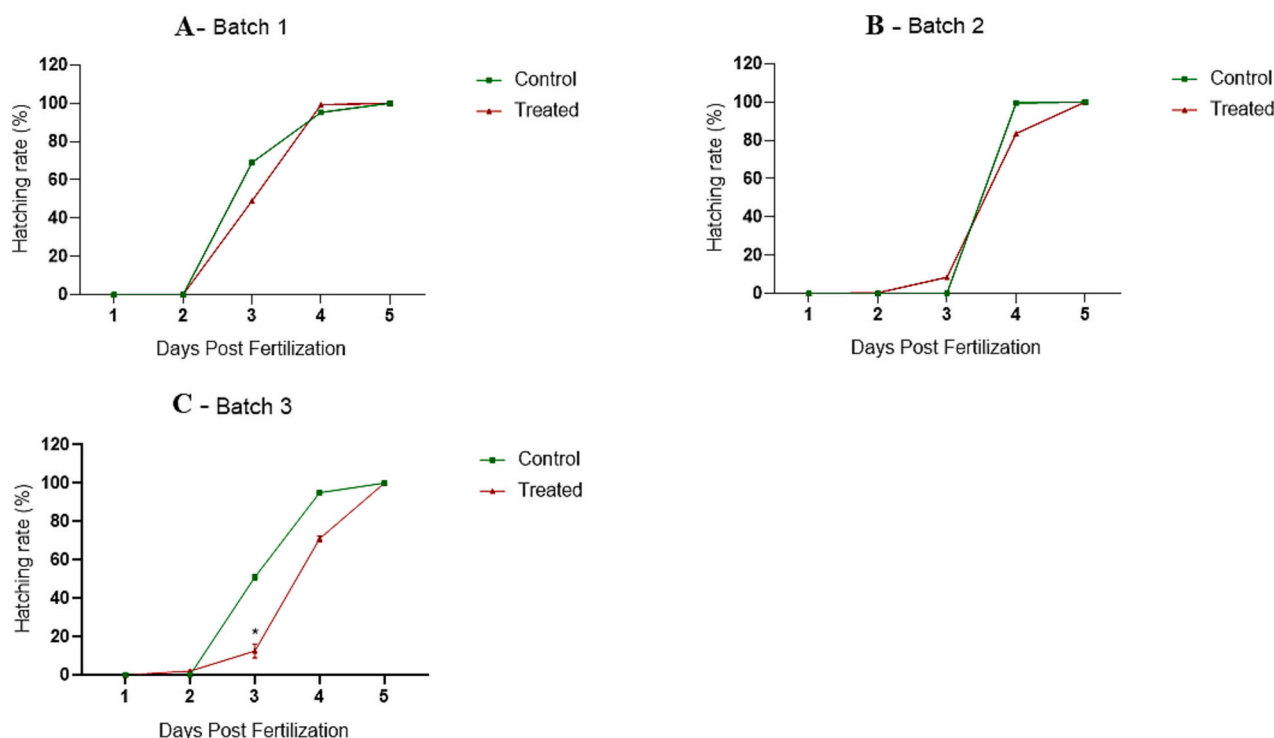


Fig. 5. Comparative analysis of hatching rate in progeny of control and exposed fish bred on 10th (A- Batch 1), 20th (B- Batch 2) and 30th (C- Batch 3) day of exposure. * $p = 0.012$; ($n = 100$).

EMF exposure, and antioxidant supplementation was found to mitigate some of these effects (Alchalabi et al., 2016). Furthermore, prenatal exposure studies indicate that RF-EMR can disrupt fetal development, causing uterine pathologies, fetal resorption, and altered implantation

patterns (Sundaram et al., 2025). These findings highlight the significant risks that EMF exposure may pose to female reproductive health, necessitating further exploration of its long-term effects.

Also, several studies have reported EMF induced damage to the male

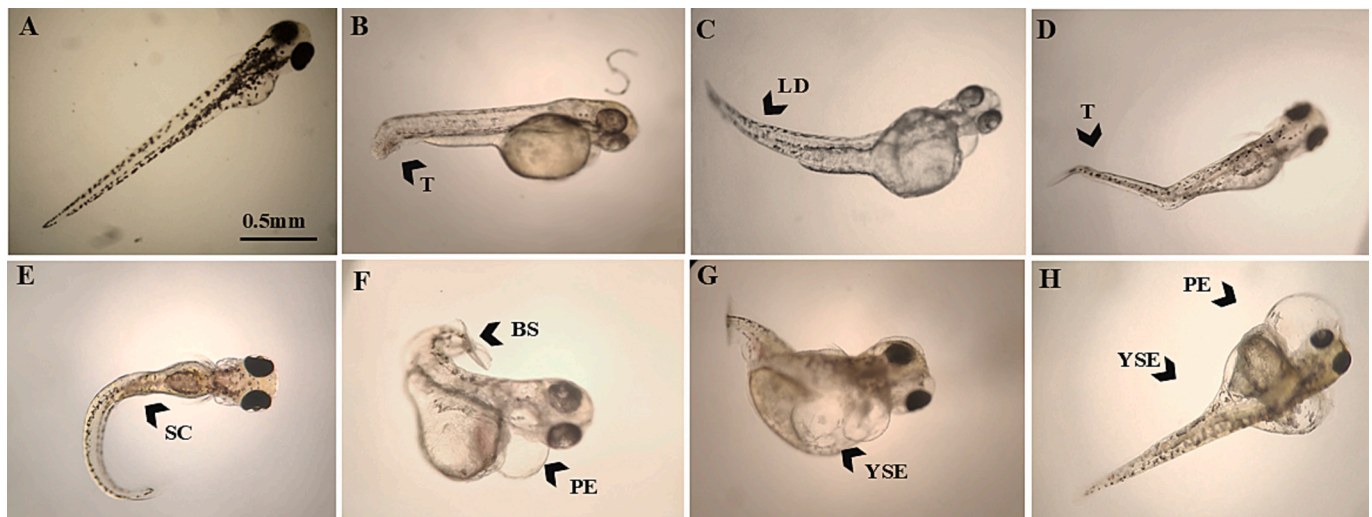


Fig. 6. Developmental deformities in progeny of control and offsprings of exposed parents. A- control (B and C) Batch 1, (D and E) Batch 2, (F to H) Batch 3. YSE- Yolk sac edema, SC- Scoliosis, BS- Bent Spine, T- Tail kink, PE- Pericardial edema; (n = 40).

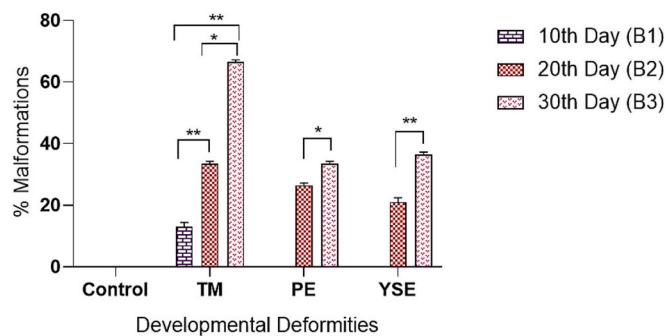


Fig. 7. Comparison of Malformations (%) of developmental deformities in progeny of control and exposed fish bred on 10th (Batch 1), 20th (Batch 2) and 30th (Batch 3) day of exposure (TM-Tail malformation, PE- Pericardial edema, YSE- Yolk sac edema). *p < 0.05, **p < 0.01, ***p < 0.001; (n = 40).

reproductive system. Changes in sperm head morphology, impaired acrosomal reactions, and increased DNA fragmentation have been reported previously in-vitro as well as in-vivo studies (Falzone et al., 2008; Sterling et al., 2022). Exposure to RF-EMR from telecommunication base stations was reported to cause testicular damage characterised by reduced testicular weight, disorganization of seminiferous tubules,

depletion of germ cells, and arrest of spermatogenic maturation in rats (Adebayo et al., 2019). Further, several other studies have documented developmental impairments following prenatal exposure, including reduced fertilization rates, delayed embryo development, and increased rates of developmental arrest (Chen et al., 2021; Seify et al., 2024). In rodents, fetal growth restriction, congenital malformations and reduced viability were reported (Saygin et al., 2018). Similar findings have been observed in frogs wherein EMF exposure resulted in reduced hatching rates and morphological defects (Boga et al., 2016) and decreased mating success in queen honey bees (Odemer and Odemer, 2019). In our present findings too, the RF-EMR exposure induced pronounced degenerative alterations in zebrafish testes, including seminiferous tubule disorganization, vacuolization, and loss of spermatogenic cells. Quantitative analysis confirmed a significant reduction in spermatogonia and spermatozoa, indicating disrupted spermatogenesis and impaired testicular integrity. Similar testicular degeneration has been reported in mammals, where prolonged 2.45 GHz Wi-Fi exposure caused decreased germ cell layers, epithelial disruption, and elevated caspase-3 activity, reflecting apoptosis within seminiferous tubules (Shokri et al., 2015; Dasdag et al., 2015). These changes are primarily linked to RF-EMR-induced oxidative stress, lipid peroxidation, and mitochondrial dysfunction, which trigger germ-cell apoptosis. The parallel between zebrafish and mammalian responses suggests a conserved vulnerability of testicular tissue to RF-EMR-mediated oxidative and apoptotic injury,

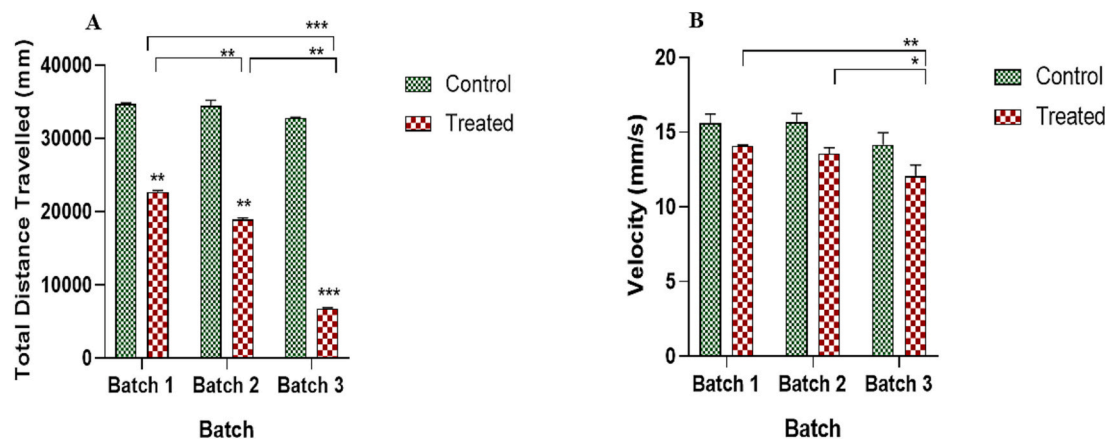


Fig. 8. Comparative analysis of locomotion activity (distance travelled in mm) and Velocity (mm/s) in progeny of control and exposed fish bred on 10th (Batch 1), 20th (Batch 2) and 30th (Batch 3) day of exposure. *p < 0.05, **p < 0.01, ***p < 0.001; (n = 10).

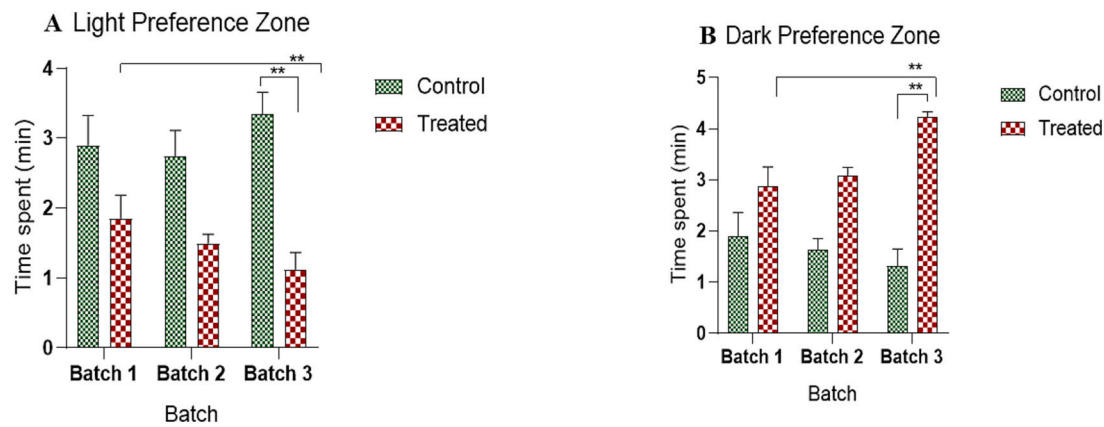


Fig. 9. Comparative analysis of zone occupancy by zebrafish larvae in progeny of control and exposed fish bred on 10th (Batch 1), 20th (Batch 2) and 30th (Batch 3) day of exposure. ** $p < 0.01$; ($n = 6$).

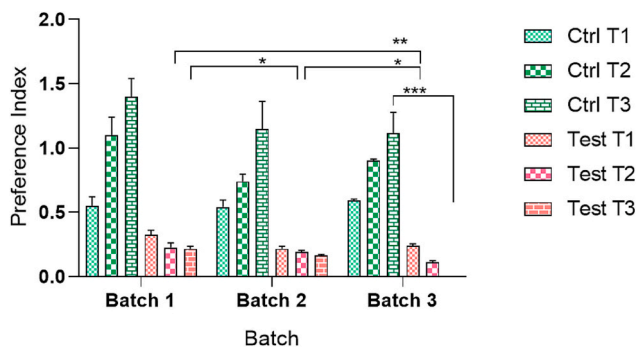


Fig. 10. NOR test - Comparative analysis of PI (Preference index) value for T1, T2, T3 (30, 60 and 90 s respectively) in progeny of control and exposed fish bred on 10th (Batch 1), 20th (Batch 2) and 30th (Batch 3) day of exposure. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ($n = 6$).

highlighting potential reproductive risks associated with sustained Wi-Fi exposure.

In our study, exposure to Wi-Fi-induced RF-EMR caused significant cellular and functional changes within the testicular architecture observed at the end of 30 day exposure. Further the progeny of exposed fish, group B1 exhibited only tail malformations, whereas groups B2 and B3 larvae displayed significantly higher incidences of anomalies such as yolk sac edema, pericardial edema, spinal curvature, and tail kinks. The severity and frequency of these defects increased with longer exposure durations. These findings indicate that prolonged parental exposure to Wi-Fi may adversely affect gonadal function and germ cell integrity, thereby contributing to a higher incidence of developmental malformations in the offspring. The vulnerability of gonadal tissue in both the male and female exposed fish in our study can be attributed to the ability of RF-EMR to induce oxidative stress, which in turn could have caused mitochondrial and DNA damage. Since gonadal tissues undergo continuous cycles of cell division in reproductively active animals, they are likely to be more sensitive to such insults, thereby transmitting detrimental effects to the next generation.

To assess neurodevelopmental integrity, a series of behavioral assays were conducted on 10 dpf larvae. The locomotion test revealed that EMF-derived larvae exhibited significantly reduced travel distance and average velocity compared to controls, indicating potential deficits in motor coordination or neuromuscular development. Such impairments could be attributed to EMF-induced alterations in neuronal ion channel regulation or neurotransmitter synthesis, as suggested in previous studies (Hu et al., 2021). In a previous report (Khira and Uggini, 2024) an exposure to 900–1800 MHz RF-EMR from mobile phones led to

significant variations in locomotion patterns particularly when exposure commenced at 1hpf in zebrafish embryos. Further, scototaxis behavior in all B1, B2 and B3 displayed increased anxiety-like behavior, preferring darker zones and spending more time along the periphery, which is a classic indicator of stress-induced behavioral inhibition. These findings mirror those of Liu et al. (2016), who demonstrated that larval zebrafish subjected to neurotoxicants exhibit similar scototaxis patterns due to impaired dopaminergic signaling. In the novel tank recognition test, control larvae actively explored their surroundings, while test larvae showed less interest or cognitive involvement. Findings across varied exposure paradigms emphasize the inherent sensitivity of the nervous system to RF-EMR during the early embryonic development. In various other reports, behavioral effects of RF-EMR, encompassing impacts on learning, memory, anxiety and locomotion were correlated to oxidative stress, ion channel disruption, and dysregulation of neurotransmitter systems. 900 MHz radiation has been shown to alter neurobehavioral performance, spatial memory, and induce hippocampal morphological changes in rodent models (Narayanan et al., 2025). Together, the observed changes in the behavior could be attributed to a combination of oxidative, electrophysiological and developmental disruptions that interfere with normal neuronal maturation and signaling during embryogenesis.

These observed transgenerational effects, particularly concerning offspring mortality and neurobehavioral phenotypes, strongly suggest that parental exposure to RF-EMR can confer heritable vulnerabilities or modify developmental trajectories in subsequent generations. Environmentally induced epigenetic transgenerational inheritance, involving heritable alterations in DNA methylation, histone modifications, and non-coding RNAs within the germline, has been comprehensively documented in response to diverse environmental stressors (Skinner, 2011; Skinner et al., 2010; Krasteva, 2024). Such epigenetic alterations can be faithfully transmitted across generations, influencing gene expression and phenotypic outcomes even in the absence of continued direct exposure to the initiating stressor. This mechanism could elucidate how parental RF-EMR exposure precipitates the observed developmental and neurobehavioral changes in the progeny.

Our findings are consistent with an expanding body of research indicating that exposure to electromagnetic fields may damage gonadal histoarchitecture and therefore could cause transgenerational effects such as physical deformities and neurobehavioral impairments. These impairment are likely driven by two factors. First, direct effects of oxidative stress on the parental germline cells compromising mitochondrial metabolism, leading to defective gametes that predispose embryos to reduced developmental competence causing embryo lethality and lethargy. Second, transgenerational effects stemming from disrupted neuronal development leading to functional deficits such as reduced motor activity, cognitive decline, and abnormal behavioral

responses.

Emerging evidence in humans supports the mechanistic relevance of RF-EMF induced oxidative stress observed in experimental models. In vitro studies on human spermatozoa have demonstrated elevated reactive oxygen species (ROS), lipid peroxidation, and DNA fragmentation after exposure to mobile phone frequencies, mirroring the oxidative and genotoxic alterations reported in rodents (Schuermann and Mevissen, 2021). Epidemiological data also indicate potential associations between intensive mobile phone use and reduced sperm motility or viability, although confounding variables such as lifestyle and localized thermal effects complicate causal inference. Evidence for heritable or multigenerational effects in humans remain insufficient; however, animal data showing germline oxidative damage and epigenetic modulation highlight the importance of further longitudinal and mechanistic studies to assess reproductive risks across generations. Although *Danio rerio* functions as a model organism, its significant genetic and physiological homologies with humans render these findings highly relevant for deciphering broader implications for public health. Given the escalating and persistent human exposure to EMFs originating from wireless routers, mobile phones, and other electronic devices, our results raise substantial concerns regarding potential reproductive and neurological risks.

5. Conclusion

This study demonstrates that parental exposure to Wi-Fi induced RF-EMR results in significant transgenerational impacts in *Danio rerio*. We observed a clear degradation in parental reproductive health evidenced by histological alterations in testicular and ovarian tissue. Furthermore, the offspring of these exposed fish exhibited increased mortality rates and visually apparent developmental abnormalities, which were more pronounced as the exposure duration increased. Significant neuro-behavioral deficits, including impaired locomotion, heightened anxiety-like behavior, and reduced recognition memory were also noticed in the offspring born to the exposed fish. These findings collectively underscore the significant biological impact of EMR exposure, emphasizing its potential to not only impair adult reproductive function but also to induce adverse developmental and neurobehavioral outcomes in the next generation. Given the increasing human and environmental exposure to the electromagnetic fields, these results highlight the urgent need for more stringent biological safety standards and support the call for comprehensive, long-term research into the transgenerational effects of RF-EMR.

CRediT authorship contribution statement

Jahnvi Mehta: Writing – original draft, Methodology, Formal analysis. **Rifat Khira:** Writing – review & editing. **Swati Fumakiya:** Writing – review & editing, Formal analysis. **Pranjal Sharma:** Methodology, Investigation. **Aditi Punekar:** Writing – review & editing. **Charmi Jain:** Methodology. **Gowri K. Uggini:** Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Ethical statement

Wild type zebrafish were procured from a certified supplier and maintained and bred as per standard laboratory protocol by the guidelines mentioned in CCSEA, Registration number - 827/GO/Re/S/04/CCSEA. Protocols followed in the current study were approved by the Institutional Animal Ethics Committee (IAEC No. Z/IAEC-3/10–2019) of the Department of Zoology, Faculty of Science, The Maharaja Sayajirao University of Baroda.

Declaration of competing interest

The authors declare no known potential personal or financial conflict of interest.

Acknowledgements

Authors JM and SF would like to thank for the senior research fellowship received through CSIR-UGC NET. We thank RCC, The Maharaja Sayajirao University of Baroda for the financial assistance provided through seed grant No. GCU/RDC/Dir./2024-25/41/18. We acknowledge Dr. Rajnikant Makwana and his lab, Department of Physics, Faculty of Science, MSU for his support with exposure related calculations.

Data availability

Data will be made available on request.

References

- Adebayo, E.A., Adeayo, A.O., Ogundiran, M.A., Olabisi, O., 2019. Bio-physical effects of radiofrequency electromagnetic radiation (RF-EMR) on blood parameters, spermatozoa, liver, kidney and heart of albino rats. *Journal of King Saud University-Science* 31 (4), 813–821. <https://doi.org/10.1016/j.jksus.2018.11.007>.
- Alchalabi, A.S., Aklilu, E., Malek, F., Ronald, S.H., Khan, M.A., 2016. Different periods of intrauterine exposure to electromagnetic field: influence on female rats' fertility, prenatal and postnatal development. *Asian Pac. J. Reprod.* 5 (1), 14–23. <https://doi.org/10.1016/j.apjr.2015.12.003>.
- Asghari, A., Khaki, A.A., Rajabzadeh, A., Khaki, A., 2016. A review on electromagnetic fields (EMFs) and the reproductive system. *Electron. Physician* 8 (7), 2655–2662. <https://doi.org/10.19082/2655>.
- Bai, Y., Liu, H., Huang, B., Wagle, M., Guo, S., 2016. Identification of environmental stressors and validation of light preference as a measure of anxiety in larval zebrafish. *BMC Neurosci.* 17, 1–12. <https://doi.org/10.1186/s12868-016-0298-z>.
- Boga, A., Emre, M., Sertdemir, Y., Uncu, I., Binokay, S., Demirhan, O., 2016. Effects of GSM-like radiofrequency irradiation during the oogenesis and spermiogenesis of *Xenopus laevis*. *Ecotoxicol. Environ. Saf.* 129, 137–144. <https://doi.org/10.1016/j.ecoenv.2016.03.015>.
- Burcu, A., Nevin, E., Ilkay, A., Amac, K., Alper, B.H., Muge, K., 2020. The effects of prenatal and postnatal exposure to electromagnetic field on rat ovarian tissue. *Toxicol. Ind. Health* 36 (12), 1010–1018. <https://doi.org/10.1177/0748233720973136>.
- Chen, C., Ma, Q., Deng, P., Lin, M., Gao, P., He, M., Zhang, L., 2021. 1800 MHz radiofrequency electromagnetic field impairs neurite outgrowth through inhibiting EphA5 signaling. *Front. Cell Dev. Biol.* 9, 657623. <https://doi.org/10.3389/fcell.2021.657623>.
- Dasdag, S., Taş, M., Akdag, M.Z., Yegin, K., 2015. Effect of long-term exposure of 2.4 GHz radiofrequency radiation emitted from Wi-fi equipment on testes functions. *Electromagn. Biol. Med.* 34 (1), 37–42. <https://doi.org/10.3109/15368378.2013.869752>.
- Dasgupta, S., Wang, G., Simonich, M.T., Zhang, T., Truong, L., Liu, H., Tanguay, R.L., 2020. Impacts of high dose 3.5 GHz cellphone radiofrequency on zebrafish embryonic development. *PLoS One* 15 (7), e0235869. <https://doi.org/10.1371/journal.pone.0235869>.
- de Gannes, F.P., Billaudel, B., Haro, E., Taxile, M., Le Montagner, L., Hurtier, A., Lagroye, I., 2013. Rat fertility and embryo fetal development: influence of exposure to the Wi-fi signal. *Reprod. Toxicol.* 36, 1–5. <https://doi.org/10.1016/j.reprotox.2012.11.003>.
- Dongus, S., Jalilian, H., Schürmann, D., Rösli, M., 2022. Health effects of WiFi radiation: a review based on systematic quality evaluation. *Crit. Rev. Environ. Sci. Technol.* 52 (19), 3547–3566. <https://doi.org/10.1080/10643389.2021.1951549>.
- Falzone, N., Huyser, C., Fourie, F., Toivo, T., Leszczynski, D., Franken, D., 2008. In vitro effect of pulsed 900 MHz GSM radiation on mitochondrial membrane potential and motility of human spermatozoa. *Bioelectromagnetics: Journal of the Bioelectromagnetics Society* 29 (4), 268–276. <https://doi.org/10.1002/bem.20390>.
- Hosseini, M.A., Hosseini, A., Jarideh, S., Argasi, H., Shekoohi-Shooli, F., Zamani, A., Haghani, M., 2019. Evaluating short-term exposure to wi-fi signals on students' reaction time, short-term memory and reasoning ability. *Radiat. Prot. Dosim.* 187 (3), 279–285. <https://doi.org/10.1093/rpd/ncz162>.
- Hu, C., Zuo, H., Li, Y., 2021. Effects of radiofrequency electromagnetic radiation on neurotransmitters in the brain. *Front. Public Health* 9, 691880. <https://doi.org/10.3389/fpubh.2021.691880>.
- Khira, R., Uggini, G.K., 2024. Effects of non-ionizing radio frequency electromagnetic radiation on the development and behavior of early embryos of *Danio rerio*. *Electromagn. Biol. Med.* 43 (3), 156–163. <https://doi.org/10.1080/15368378.2024.2352429>.
- Krasteva, M.E., 2024. Environmental stress, epigenetic modifications, adaptation, and disease: a fine interplay. Beyond the blueprint-decoding the elegance of gene

- expression: decoding the elegance of gene expression, 27. <https://doi.org/10.1017/S0967199424000042>.
- Laudisi, F., Sambucci, M., Nasta, F., Pinto, R., Lodato, R., Altavista, P., Pioli, C., 2012. Prenatal exposure to radiofrequencies: effects of WiFi signals on thymocyte development and peripheral T cell compartment in an animal model. *Bioelectromagnetics* 33 (8), 652–661. <https://doi.org/10.1002/bem.21733>.
- Liu, X., Lin, J., Zhang, Y., Peng, X., Guo, N., Li, Q., 2016. Effects of diphenylhydantoin on locomotion and thigmotaxis of larval zebrafish. *Neurotoxicol. Teratol.* 53, 41–47. <https://doi.org/10.1016/j.ntt.2015.11.008>.
- Maack, G., Segner, H., 2003. Morphological development of the gonads in zebrafish. *J. Fish Biol.* 62 (4), 895–906. <https://doi.org/10.1046/j.1095-8649.2003.00074.x>.
- Meyer, F., Forman, H.J., Fragoulis, A., et al., 2024. The effects of radiofrequency electromagnetic field exposure on biomarkers of oxidative stress in vivo and in vitro experimental studies: a systematic review. *Environ. Int.* 168, 107393. <https://doi.org/10.1016/j.envint.2023.107393>.
- Mohamed, A.O., Abdel-Hafez, S.M.N., Ibrahim, R.A., Refaai, R.A., 2022. The possible effects of electromagnetic waves of Wi-fi router on the hippocampus of male rats. *Minia J. Med. Res.* 33 (2), 1–6. <https://doi.org/10.21608/mjmr.2022.220816>.
- Montzeri, A., Pooladi, M., Odoumizadeh, M., Nazarian, N., Karani, S., 2019. The effects of WiFi network (2.45 GHz) on rats with induced stroke associated with an increased risk of heart attack. *Sciences* (2). <https://doi.org/10.22037/jps.v10i2.24145>.
- Narayanan, S.N., Kumar, R.S., Kumar, N., Prabhakar, P., Nayak, S.B., Bhat, P.G., 2025. Possible effects of radiofrequency electromagnetic radiation on contextual fear conditioning, hippocampal perivascular space, apoptosis and adrenal gland microarchitecture in rats. *Behav. Brain Res.* 481, 115424. <https://doi.org/10.1016/j.bbr.2025.115424>.
- Odemer, R., Odemer, F., 2019. Effects of radiofrequency electromagnetic radiation (RF-EMF) on honey bee queen development and mating success. *Sci. Total Environ.* 661, 553–562. <https://doi.org/10.1016/j.scitotenv.2019.01.154>.
- Othman, H., Ammari, M., Sakly, M., Abdelmelek, H., 2017a. Effects of repeated restraint stress and WiFi signal exposure on behavior and oxidative stress in rats. *Metab. Brain Dis.* 32, 1459–1469. <https://doi.org/10.1007/s11011-017-0016-2>.
- Othman, H., Ammari, M., Sakly, M., Abdelmelek, H., 2017b. Effects of prenatal exposure to WiFi signal (2.45 GHz) on postnatal development and behavior in rat: influence of maternal restraint. *Behav. Brain Res.* 326, 291–302. <https://doi.org/10.1016/j.bbr.2017.03.011>.
- Panagopoulos, D.J., Karabarbounis, A., Yakymenko, I., Chrousos, G.P., 2021. Human-made electromagnetic fields: ion forced-oscillation and voltage-gated ion channel dysfunction, oxidative stress and DNA damage (review). *Int. J. Oncol.* 59, 92. <https://doi.org/10.3892/ijo.2021.5272>.
- Poulletier de Gannes, F., Haro, E., Hurtier, A., Taxile, M., Athane, A., Ait-Aissa, S., Lagroye, I., 2012. Effect of in utero W i-F i exposure on the pre-and postnatal development of rats. *Birth Defects Res. B Dev. Reprod. Toxicol.* 95 (2), 130–136. <https://doi.org/10.1002/bdrb.20346>.
- Poulletier de Gannes, F., Billaudel, B., Haro, E., Taxile, M., Le Montagner, L., Hurtier, A., Ait Aissa, S., Masuda, H., Percherancier, Y., Ruffié, G., Dufour, P., Veyret, B., Lagroye, I., 2013. Rat fertility and embryo fetal development: influence of exposure to the Wi-Fi signal. *Reprod. Toxicol. (Elmsford, N.Y.)* 36, 1–5. <https://doi.org/10.1016/j.reprotox.2012.11.003>.
- Saili, L., Hanini, A., Smirani, C., Azzouz, I., Azzouz, A., Sakly, M., Bouslama, Z., 2015. Effects of acute exposure to WIFI signals (2.45 GHz) on heart variability and blood pressure in albinos rabbit. *Environ. Toxicol. Pharmacol.* 40 (2), 600–605. <https://doi.org/10.1016/j.etap.2015.08.015>.
- Sambucci, M., Laudisi, F., Nasta, F., Pinto, R., Lodato, R., Altavista, P., Pioli, C., 2010. Prenatal exposure to non-ionizing radiation: effects of WiFi signals on pregnancy outcome, peripheral B-cell compartment and antibody production. *Radiat. Res.* 174 (6a), 732–740. <https://doi.org/10.1667/RR2255.1>.
- Sambucci, M., Laudisi, F., Nasta, F., Pinto, R., Lodato, R., Lopresto, V., Pioli, C., 2011. Early life exposure to 2.45GHz WiFi-like signals: Effects on development and maturation of the immune system. *Prog. Biophys. Mol. Biol.* 107 (3), 393–398. <https://doi.org/10.1016/j.pbiomolbio.2011.08.012>.
- Saygin, M., Ozmen, O., Erol, O., Ellidag, H.Y., Ilhan, I., Aslankoc, R., 2018. The impact of electromagnetic radiation (2.45 GHz, Wi-fi) on the female reproductive system: the role of vitamin C. *Toxicol. Ind. Health* 34 (9), 620–630. <https://doi.org/10.1177/0748233718775540>.
- Schuermann, D., Mevissen, M., 2021. Manmade electromagnetic fields and oxidative stress biological effects and consequences for health. *Int. J. Mol. Sci.* 22 (7), 3772. <https://doi.org/10.3390/ijms22157775>.
- Seify, M., Khalili, M.A., Anbari, F., Koohestanidehaghi, Y., 2024. Detrimental effects of electromagnetic radiation emitted from cell phone on embryo morphokinetics and blastocyst viability in mice. *Zygote* 32 (2), 149–153. <https://doi.org/10.1177/0748233718775540>.
- Shokri, S., Soltani, A., Kazemi, M., Sardari, D., Mofrad, F.B., 2015. Effects of Wi-fi (2.45 GHz) exposure on apoptosis, sperm parameters and testicular histomorphometry in rats: a time course study. *Cell Journal (Yakhteh)* 17 (2), 322. <https://doi.org/10.22074/cellj.2016.3740>.
- Skinner, M.K., 2011. Environmental epigenetic transgenerational inheritance and somatic epigenetic mitotic stability. *Epigenetics* 6 (7), 838. <https://doi.org/10.4161/epi.6.7.16537>.
- Skinner, M.K., Manikkam, M., Guerrero-Bosagna, C., 2010. Epigenetic transgenerational actions of environmental factors in disease etiology. *Trends Endocrinol. Metab.* 21 (4), 214–222. <https://doi.org/10.1016/j.tem.2009.12.007>.
- Slaoui, M., Fiette, L., 2010. Histopathology procedures: From tissue sampling to histopathological evaluation. In: *Drug Safety Evaluation: Methods and Protocols*. Humana Press, Totowa, NJ, pp. 69–82. https://doi.org/10.1007/978-1-60761-849-2_4.
- Sterling, L., Harris, L.R., Carroll, K., 2022. The effects of wireless devices on male reproductive health: a literature overview. *Revista Internacional de Andrología* 20 (3), 196–206. <https://doi.org/10.1016/j.androl.2020.10.004>.
- Sundaram, V.A., Saravanan, B., Durairaj, J.R., Balamurugan, B.S., Marimuthu, M.M.C., Chopra, H., 2025. The role of environmental toxins in infertility: insights from cutting-edge research. *Scr. Med.* 56 (2), 383–393. <https://doi.org/10.5937/scriptamed56-53922>.
- Wu, H., Min, D., Sun, B., Ma, Y., Chen, H., Wu, J., Wang, P., 2023. Effect of WiFi signal exposure in utero and early life on neurodevelopment and behaviors of rats. *Environ. Sci. Pollut. Res.* 30 (42), 95892–95900. <https://doi.org/10.1007/s11356-023-29159-4>.