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Impact of Short-Term Ultraviolet (UV) Radiation Exposure on *Paramecium* Behavior, Viability, Proliferation and Implications for Freshwater Ecosystem Health

Nageswara Rao Amanchi and Ambati Sneha
Ecotoxicology Lab, Department of Zoology,
University College of Science, Osmania University, Hyderabad-500 007, India
E-mail: bowmibannu@gmail.com

Abstract: *Paramecium caudatum*, a well-established freshwater protozoan model, was employed to assess the sub-lethal and lethal effects of ultraviolet (UV) radiation exposure at 254 nm. *Paramecia* were exposed to varying durations of UV light ranging from 1 to 5 minutes, and observed for behavioral and physiological changes over a period of 96 hours. Short-term exposure (1-3 minutes) resulted in no mortality and retained normal motility and morphology. However, 4-minute exposure induced noticeable stress responses, including reduced swimming speed, disrupted locomotion patterns, and partial loss of cellular activity, with approximately 50% of individuals becoming inactive. The most severe effects were recorded following 5-minute exposure, where paramecia exhibited pronounced morphological deformities such as swelling, elongation, and loss of symmetry, along with pigmentation changes such as darkening and spotting of cytoplasm, loss of shape and structure, impaired coordination, and complete mortality by 24 hours post-exposure. Due to its ecological importance and sensitivity to UV radiation *Paramecium* serves as a valuable bioindicator for assessing the environmental impacts of increasing UV radiation associated with climate change. Additionally, it contributes to SDG 14 (Life below Water) by emphasizing that the UV sensitivity of freshwater protozoa reflects broader risks to aquatic microbial communities.

Keywords: *Paramecium caudatum*, Ultraviolet (UV) radiation, Environmental stress, Climate change

As global temperatures continue to rise, the impacts of climate change and ozone depletion pose significant threats to ecosystems worldwide, particularly freshwater environments. In this context, *P. caudatum*, a freshwater ciliate and established model organism, serves as a valuable bioindicator for assessing environmental stressors. Its sensitivity to ultraviolet (UV) radiation intensified by ozone layer depletion makes it especially vulnerable to DNA damage and membrane disruption, often resulting in elevated rates of cell mortality (Campbell and Romero 2009). Additionally, climate change can exacerbate the bioavailability and toxicity of pollutants such as pesticides and heavy metals, further endangering aquatic organisms. *P. caudatum* has been extensively employed in toxicological studies to evaluate the sub-lethal effects of these environmental contaminants, including drugs and natural food dyes, as well as to develop behavioral and physiological biomarkers (Venkateswara Rao et al., 2012, Hussain et al., 2008, Houneida et al., 2012, Pokhrel 2015). Its structural simplicity, short generation time (4-8 hours), ease of cultivation, and large cell size make it a practical and cost-effective model for laboratory research and bioassays (Mansano et al., 2016, Zhang 2022). Ubiquitous in stagnant and flowing freshwater systems, Paramecium plays a critical ecological role by influencing trophic dynamics and maintaining ecosystem balance (Potekhin et al., 2020). These qualities make it a reliable sentinel species in freshwater ecology, particularly as environmental stressors intensify due to climate change.

Paramecium has a long history as a model organism in cellular and genetic research, offering insights into intracellular differentiation, senescence, inheritance, and nucleocytoplasmic interactions (Houneida et al., 2012). Its ability to undergo autogamy and its interactions with symbiotic bacteria, viruses, and algae provide avenues for investigating host-microbe relationships (Sbartai Ibtissem et al., 2009). Studies examining its responses to environmental pollutants have revealed significant changes in motility, chemotaxis, phagocytosis, viability, and population dynamics. Notably, exposure to pesticides can lead to a concentration-dependent cascade of cellular abnormalities, including blistered and ruptured membranes, cell lysis, protoplasmic disintegration, and protein coagulation (Venkateswara Rao et al., 2006, Vijayakumar and Amanchi 2025). As climate change continues to amplify ecological stress, the role of *P. caudatum* in monitoring environmental health becomes increasingly crucial. The objective of this study is to investigate the effects of ultraviolet (UV) light exposure on *P. caudatum* by assessing its behavioral responses, survival rate, and reproductive capacity. Together, these assessments will provide a comprehensive understanding of how UV light affects the physiology and ecology of *P. caudatum* (Valentine et al., 2021).

MATERIAL AND METHODS

Freshwater samples were collected from the vicinity of Osmania University (GPS coordinates are 17.413333° N, 78.528611° E), Hyderabad, for the isolation, identification, and cultivation of *P. caudatum* for experimental analysis. A droplet from these water samples was extracted and examined under a microscope to confirm the presence of *Paramecium*. For culturing, a standard hay infusion medium was prepared using dried hay segments (1–8 cm in length), following the protocol described by Sonneborn (1950). The medium was prepared by boiling 6 grams of dried hay leaves in one liter of distilled water, followed by cooling, filtration, and autoclaving at 15 psi for 15 minutes. After sterilization, the medium was diluted with distilled water in a 1:1 ratio and transferred into 150 ml conical flasks for culturing and sub-culturing purposes (Bick 1972). To enhance bacterial growth, which serves as a primary food source for *Paramecium* cooked lady's finger (Okra) was added to the medium. Regular cultivation of multiple isolation lines and monitoring of growth rates were carried out to ensure reliable culture conditions (Sonneborn 1950). Sub-culturing was performed every sixth day to maintain healthy and log phage culture (Amanchi and Archana 2021).

Experimental details: About 25 *Paramecium* cells were isolated from a log-phase culture and distributed into five separate cavity blocks for experimental analysis. Each block was labeled according to exposure time intervals 1, 2, 3, 4, and 5 minutes and placed inside a laminar air flow chamber under a UV light source. The blocks were positioned at 65 cm from the UV lamp emitting light at a wavelength of 254 nm (Campbell and Romero 2009). Following UV exposure, immediate observations were conducted for first four hours at 30-minute intervals, and subsequent assessments were made at 24, 48, 72, and 96 hours post-exposure. During these observation periods, both behavioral responses and cellular proliferation were recorded. Key characteristics evaluated included body shape, structure, size, color, motility, swimming pattern, speed, general movement, and mortality; all assessed manually (Venkateswara Rao et al., 2006).

RESULTS AND DISCUSSION

Paramecia exposed to UV light for 1 to 3 minutes exhibited normal activity with no signs of mortality during continuous observation over a 4-hour period, recorded at 30-minute intervals. However, significant behavioral and physiological changes were observed with longer exposure durations. Morphological deformities in body shape and structure were assessed following UV exposure, with common abnormalities including swelling, elongation along the anterior–posterior axis, and loss of overall body symmetry. Visual determination of body size revealed a consistent reduction in length accompanied by an increase in body width, suggestive of structural stress induced by UV radiation. Under normal conditions, the paramecium exhibits a transparent body; however, post-exposure individuals displayed marked changes in pigmentation, including loss of transparency, darkening, and the appearance of unusual spots, suggesting cellular damage. Behavioral responses were also significantly affected. Initially, organisms exhibited erratic movements, followed by migration toward the corners of the cavity block, presumably as an avoidance response to UV radiation. Notable alterations in swimming behavior included uncoordinated motion, circling, sinking, variations in swimming speed, and overall loss of locomotor control. In 4-minute UV exposure, the movement of paramecia became noticeably slow, with reduced spinning behavior and instances of the organisms rotating around their own axis. Approximately 50% of the observed cells became highly inactive, displaying signs of severe stress and nearing death. The most profound effects were observed following 5 minutes of UV exposure. *Paramecia* subjected to this duration showed pronounced morphological changes, including distortion of body shape, narrowing of the anterior end, and an overall loss of their typical body structure. These individuals also exhibited a drastic reduction in swimming speed, loss of orientation and coordination, and impaired movement. In 24 hours post-exposure, all paramecia subjected to the 5-minute treatment had died, indicating complete lethality at this level of UV stress.

Extensive research has demonstrated that environmental stressors, particularly ultraviolet (UV) radiation, exert profound effects on the physiology, behavior, and cellular integrity of aquatic microorganisms such as *P. caudatum* (Barbara Kammerlander, et al., 2018). UV radiation, especially at 254 nm, induces DNA damage and disrupts critical cellular structures, leading to mutations and physiological impairments that compromise essential biological functions including motility, reproduction, and survival (Kammerlander et al., 2018). Short-term UV exposure has been shown to elicit marked behavioral alterations in *Paramecium*, characterized by decreased swimming speed, disrupted locomotion patterns, loss of orientation, and diminished responsiveness to environmental stimuli such as light and food sources (Niculite et al., 2018, Arlinghaus et al., 2019). These behavioral disruptions primarily arise from UV-induced damage to the cilia, the organelles responsible for propulsion and environmental sensing, thereby impairing the organism's capacity to navigate and adapt to its surroundings effectively

Table 1. Behavioral and morphological characteristics observation in *Paramecium caudatum* following UV (254nm) exposure with different time periods

UV (254nm) exposure duration (Minutes)	Motility (Before)	Motility (After)	Movement (Before)	Movement (After)	No of paramecia (Before)	No of paramecia (After)	Body shape (Before)	Body shape (After)	Colour (Before)	Colour (After)	Observation
1	Yes	Yes	Good	Good	20±5	20±5	Slipper	Slipper	Transparent	Transparent	No Effect
2	Yes	Yes	Good	Good	20±5	20±5	Slipper	Slipper	Transparent	Transparent	No effect
3	Yes	Yes	Good	Good	20±5	20±5	Slipper	Slipper	Transparent	Transparent	No Effect
4	Yes	UV avoidance noticed	Good	Erratic and reached to corners of cavity block	20±5	20±5	Slipper	Elongated, Narrowed at anterior	Transparent	Pigmentation, Blackening of cytoplasm	Significant Behavioral changes noticed
5	Yes	UV avoidance noticed	Good	Erratic movement and loss of coordination	20±5	20±5	Slipper	Loss of symmetry, Bulged	Transparent	Spotting in cytoplasm, Blackening of cytoplasm	Significant Behavioral changes noticed

Table 2. Growth Inhibition in *Paramecium caudatum* following exposure to 254 nm UV Radiation at relative to control (n = 5)

Exposure distance	Duration (Minutes)	No. of. organisms	No. of. organisms (Growth proliferation)				No. of. organisms (% growth inhibition)			
			Control group (hrs)				Experimental group (hrs)			
			24	48	72	96	24	48	72	96
65cm	1 min	20±5	783.6 (100)	1022.8 (100)	1284.6 (100)	1558.0 (100)	438 (44.06)	342 (66.56)	159 (87.62)	13 (99.16)
65cm	2 min	20±5					352 (55.07)	345 (66.26)	97 (92.44)	12 (99.22)
65cm	3 min	20±5					317 (59.54)	308 (69.88)	125 (90.26)	15 (99.03)
65cm	4 min	20±5					247 (68.47)	151 (85.13)	82 (93.61)	08 (99.49)
65cm	5 min	20±5					Nil (100)	Nil (100)	Nil (100)	Nil (100)

(Kammerlander et al., 2018, Arlinghaus et al., 2019). Prolonged UV exposure exacerbates these deleterious effects, resulting in pronounced morphological deformities, including aberrations in body shape and loss of structural integrity, ultimately culminating in cell death (Gopi Krishna et al., 2022).

Paramecium's pivotal ecological role in freshwater systems regulating microbial populations and contributing to nutrient cycling such impairments can disrupt ecosystem function and stability (Ruben et al., 2001, Goodwin et al., 2018, Nichols et al., 2018). The sensitivity of *Paramecium* to UV-induced stress underscores its utility as a bioindicator for environmental monitoring climate change. These findings highlight that UV radiation exposure at 254 nm for 4 to 5 minutes significantly compromises *Paramecium caudatum*'s motility, viability, and reproductive capacity, with broader implications for microbial community dynamics and freshwater ecosystem health (Kammerlander et al., 2018, Niculite et al., 2018, Arlinghaus et al., 2019, Gopi Krishna et al., 2022). This study supports SDG 13 (Climate action) by demonstrating the ecological impacts of increased UV radiation, a consequence of climate change. The use of *P. caudatum* as a bioindicator highlights the potential for early detection of climate-induced stress in aquatic ecosystems. Additionally, it contributes to SDG 14 (Life below Water) by emphasizing that the UV sensitivity of freshwater protozoa reflects broader risks to aquatic microbial communities. These findings underscore the need for monitoring micro-scale biological responses to environmental change as part of global adaptation and ecosystem protection efforts.

CONCLUSION

The present study demonstrates that ultraviolet (UV) radiation at 254 nm induces significant morphological and behavioral alterations in *Paramecium caudatum*, with the severity of effects directly related to exposure duration. Short-term exposures (1–3 minutes) had negligible effects, whereas longer exposures (4–5 minutes) resulted in marked deformities, impaired motility, and ultimately, complete mortality within 24 hours. Key physiological changes included swelling, elongation, body asymmetry, pigmentation loss, and ciliary dysfunction, which collectively compromised the organism's locomotion and orientation. These effects reflect underlying cellular damage likely due to UV-induced DNA disruption and structural impairment. Furthermore, the sensitivity of *P. caudatum* to UV radiation highlights its potential as a biological marker for assessing and monitoring the health of freshwater ecosystems. These findings underscore the broader ecological consequences of increased UV exposure associated with climate change and align with Sustainable Development Goal 14 by emphasizing the vulnerability of aquatic microbial communities and the importance of early detection and adaptive ecosystem protection strategies.

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