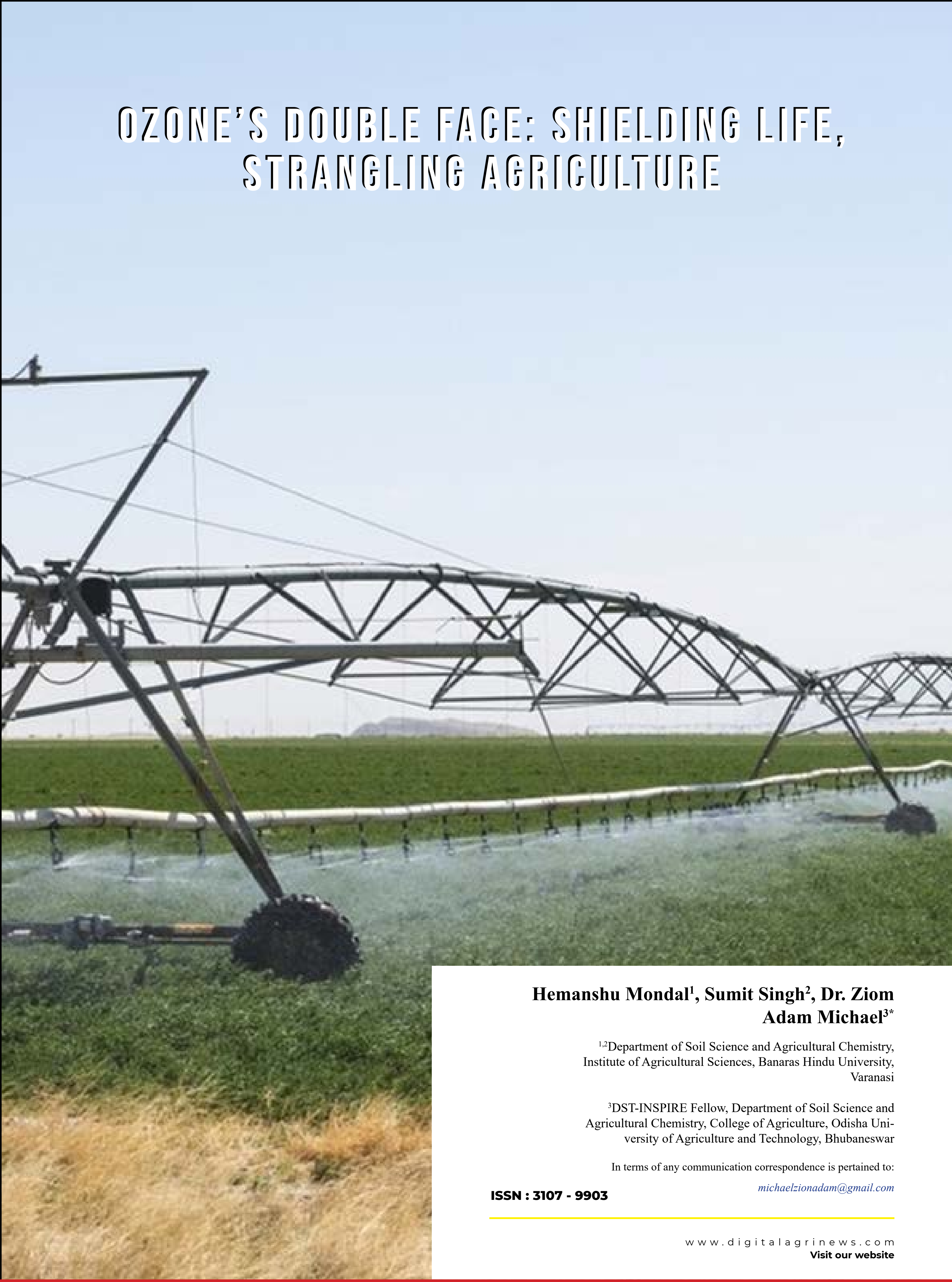
OZONE'S DOUBLE FACE: SHIELDING LIFE, STRANGLING AGRICULTURE



Hemanshu Mondal[1], Sumit Singh[2], Dr. Ziom Adam Michael[3*]

[1,2]Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi

[3]DST-INSPIRE Fellow, Department of Soil Science and Agricultural Chemistry, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar

In terms of any communication correspondence is pertained to:

michaelzionadam@gmail.com

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Ozone's Double Face: Shielding Life, Strangling Agriculture

Hemanshu Mondal[1], Sumit Singh[2], Dr. Ziom Adam Michael[3*]

[1,2]*Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi*

[3]*DST-INSPIRE Fellow, Department of Soil Science and Agricultural Chemistry, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar*

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Abstract

Tropospheric ozone (O_3) has emerged as a major limitation to agricultural productivity as high surface concentrations (40-70ppb) of ozone inhibit photosynthesis, increase leaf senescence, and reduce time to gain filler grains. In sensitive C3 crops like rice and wheat, yields have decreased (11-20%). In highly cultivated areas such as the Indo-Gangetic Plain, the phytotoxic pollutant poses a major threat to food security and farmers' incomes. Nevertheless, significant research gaps remain in the connection between crop-level physiological harm and soil biogeochemical processes and greenhouse gas feedbacks, with most assessments based on concentration-based exposure measures rather than mechanistic ones. The paper is a synthesis of experimental data from open-top chamber experiments conducted at the Indian Agricultural Research Institute and other literature on the effects of ozone on the rice-wheat agroecosystem. Controlled exposure (60-70 ppb) significantly reduced rice yield (11-12%) due to a decrease in the number of tillers, filled grains, and test weight. In contrast, in wheat-based ecosystems, lower nitrogen uptake increased soil ammonium and nitrate concentrations, resulting in a nearly 15% increase in nitrous oxide (N_2O) emissions. The results demonstrate the dual effects of ozone: decreased crop productivity and strengthened climate feedbacks, underscoring the importance of combined mitigation and adaptive agronomic practices.

Introduction: Comprehending the Dual Nature of Ozone

Ozone (O_3) is a triatomic oxygen, which can only serve a purpose in the environment in its vertical distribution in the air. In the atmosphere at high altitudes, this plays a vital protective role for life. In contrast, at ground level, it causes negative impacts, including pollution, posing a threat to agriculture, ecosystems, and climate stability. This vertical contrast gives ozone a double face. Even though stratospheric ozone depletion has been prevented by global action under the Montreal Protocol, tropospheric ozone concentrations have increased by more than 2 times since the pre-industrial period. Surface ozone is a serious threat to crop productivity and food security nowadays, yet it remains largely unaddressed, especially in rapidly growing, industrialized areas (Ma et al., 2025).

Ozone in Different Atmospheric Layers: From Pollutant to Protective Shield

Ozone's role varies greatly with altitude. In the stratosphere, an area about 10-50 km above the Earth's surface, ozone concentrations create the ozone layer, which shields Earth's living organisms from the harmful ultraviolet-B (UV-B) radiation. This process occurs when high-energy ultraviolet radiation interacts with molecular oxygen (O_2), splitting the O_2 molecules into oxygen atoms, which then recombine with O_2 to form ozone. In the latter half of the twentieth century, the release of chlorofluorocarbons (CFCs) resulted in the depletion of the ozone layer, creating the ozone hole. However, international policies have helped restore the ozone layer, with complete recovery expected in the mid-twenty-first century.

Tropospheric ozone, by comparison, is a secondary pollutant produced by a series of photochemical reactions between nitrogen oxides (NO_x), volatile organic compounds (VOCs) and methane (CH_4), along with carbon monoxide (CO) and sunlight. NO_2 (Nitrogen dioxide) is subject to photolysis, which produces atomic oxygen, which combines with the oxygen to form ozone. The disruption of the normal balance between nitric oxide and ozone in polluted atmospheres with high VOC concentrations leads to ozone accumulation. Whereas the ozone concentration in the pre-industrial period was about 10 to 15 parts per billion (ppb), current planetary values are 40 to 50 ppb, with even higher values in densely populated, highly developed areas such as the Indo-Gangetic Plain. Therefore, the same ozone that is helpful in the stratosphere is a phytotoxic pollutant in the troposphere, contributing to photochemical smog, greenhouse gas forcing, and agricultural damage.

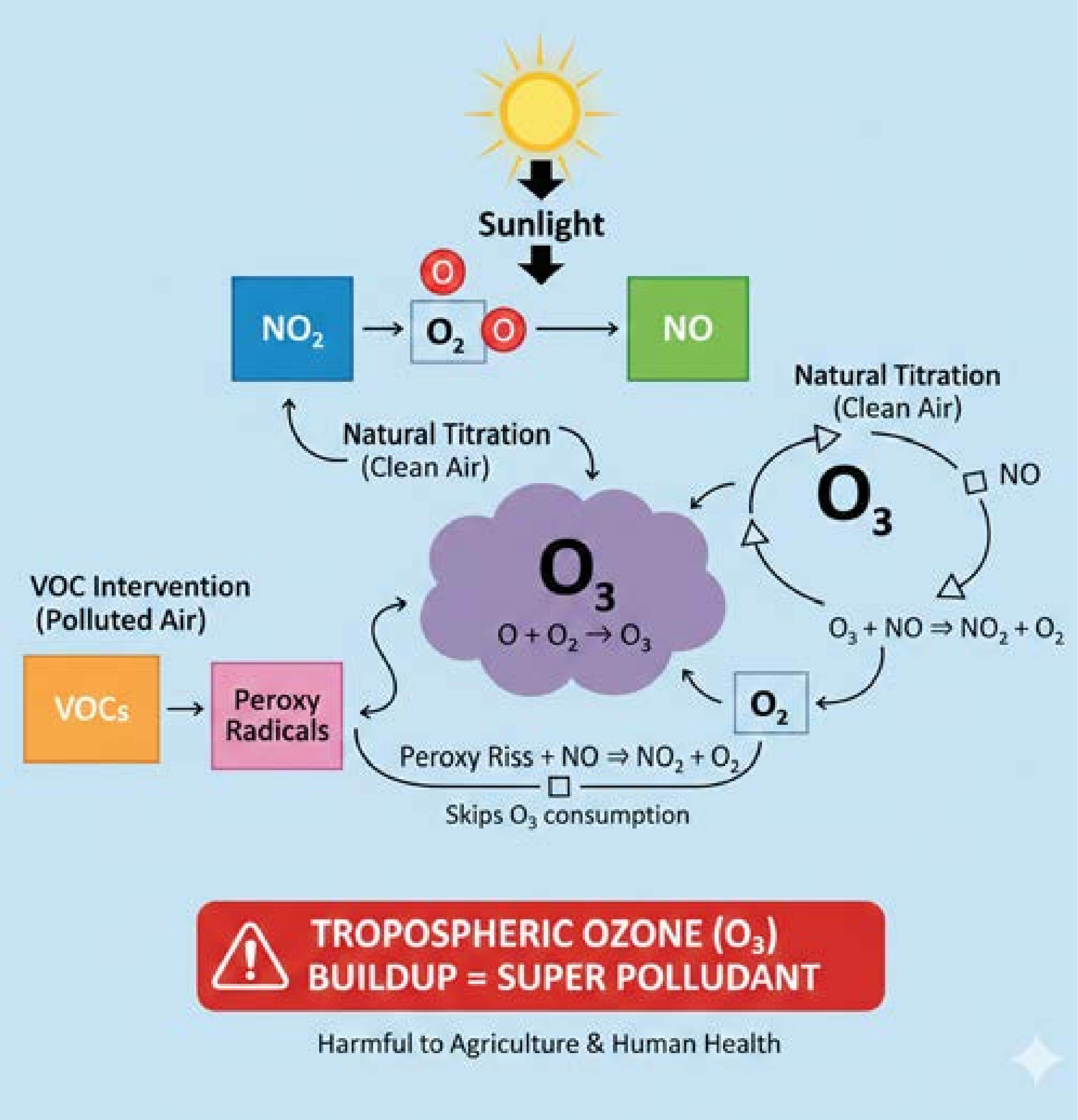

Fig. 1: Tropospheric Ozone's Photochemical Formation and Accumulation Mechanism under NO–VOC Interactions

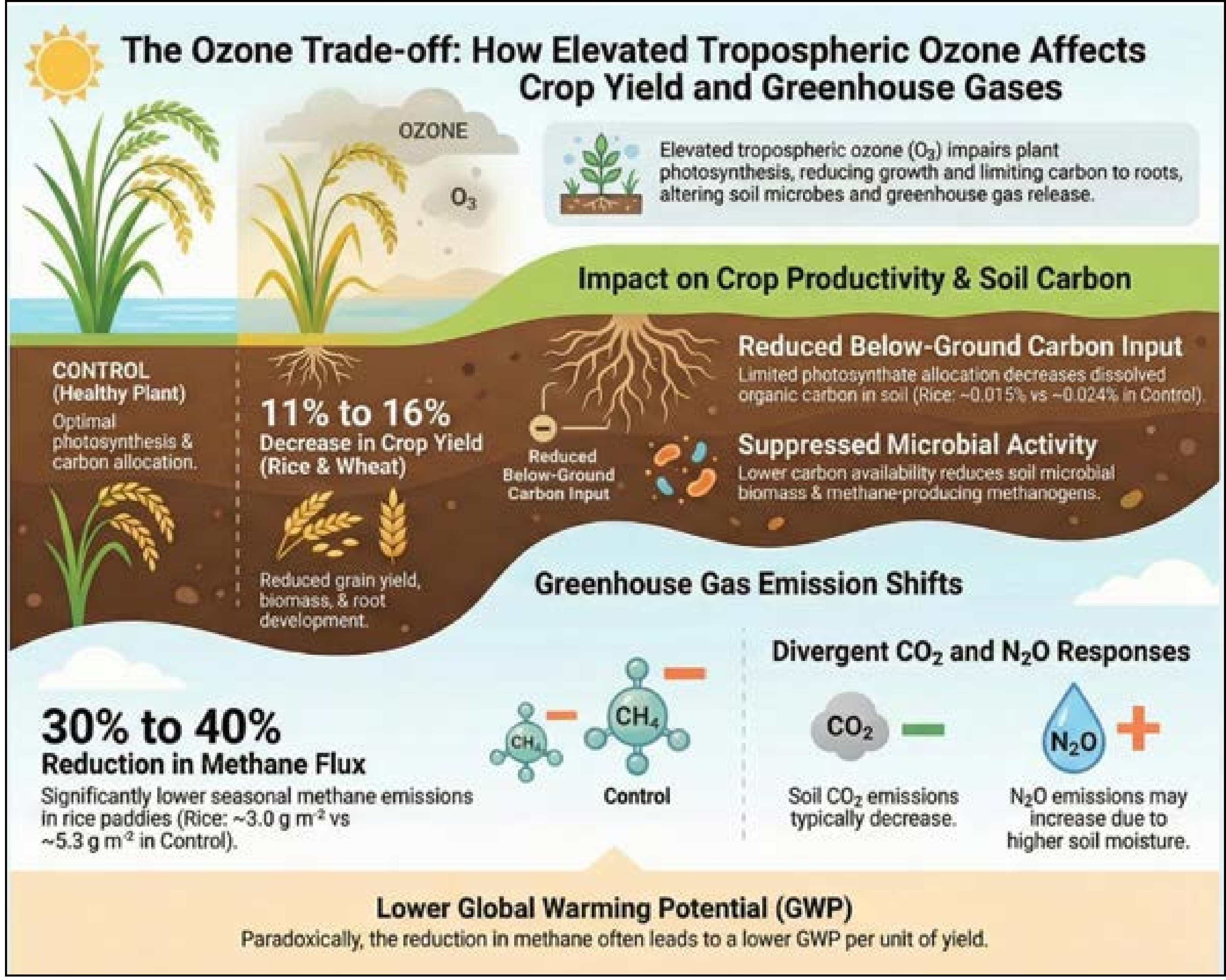

Fig. 2: Mechanistic Impact of Increased Tropospheric Ozone on Rice-Wheat Systems' Greenhouse Gas Fluxes, Soil Carbon Dynamics, and Crop Productivity

Effects of Physiology on Crop Plants

Reactive oxygen species (ROS) are produced in leaf tissues when tropospheric ozone enters plants through stomata during gas exchange. These reactive chemicals inhibit carbohydrate synthesis by damaging chloroplasts, blocking the photosynthetic electron transport chain, and decreasing Rubisco enzyme activity. Additionally, partial stomatal closure induced by ozone exposure limits carbon dioxide uptake, leading to carbon starvation. Chlorosis and early senescence, which shorten the grain-filling period, are visible symptoms.

Because they lack the carbon-concentrating mechanisms that C4 crops have, C3 crops—like rice and wheat—are especially vulnerable. Reduced biomass, poor grain development, and a notable yield decline are the cumulative results (Nowroz et al., 2024).

Rice Agroecosystems evidence

Experimentation at the Indian Agricultural Research Institute in New Delhi, using open-top chambers, showed significant damage to rice systems caused by ozone. The impacts of a high ozone concentration (around 60-70 ppb) were a 11-12% reduction in grain yield relative to the ambient environment. The most important yield parameters included the number of tillers, the number of filled grains per panicle, and test weight, all of which decreased significantly. Grain-filling was also shortened by accelerated leaf senescence. These results show that exposure to ozone, rather than variation in microclimatic conditions, was the most important cause of yield losses (Singh et al., 2015).

Nitrous Oxide Increase in Wheat Systems

In upland wheat ecosystems, ozone exposure increases nitrous oxide (N2O) emissions. Lower plant growth translates to lower nitrogen uptake, resulting in higher concentrations of ammonium and nitrate in the soil. At the same time, lower transpiration rates lead to higher soil moisture, thereby enhancing denitrification. Consequently, N2O emissions rise by 15%. This is a critical climate feedback response given N2O's high global warming potential (Hu et al., 2018).

Implications for the Economy, Policy, and Sustainability

Climate policy, farmer livelihoods, and food security are all significantly impacted by tropospheric ozone. Estimates of ozone-induced crop losses worldwide range from 79 to 121 million tonnes per year, translating into annual economic damages of roughly 11 to 18 billion US dollars. High precursor emissions and the intensive production of sensitive crops like wheat and rice make regions like East Asia and North India especially vulnerable. In areas with high population density, yield reductions endanger nutritional quality and calorie supply, in addition to lowering farmers' incomes. To deal with this challenge, a combined mitigation and adaptation framework is needed. The best way to reduce surface ozone levels is to reduce emissions of nitrogen oxides, volatile organic compounds, and methane, and mitigating methane offers particularly good prospects for reducing background ozone. At the same time, resilience to oxidative stress can be improved through agricultural adaptation strategies such as the development of ozone-tolerant cultivars, nutrient management and optimization, and diversification of cropping systems.

Conclusion

At the end, we can say Ozone is a deep paradox of the atmosphere: it protects life in the stratosphere but destroys agricultural sustainability on the ground. The empirical data on 11-20 per cent yield reduction, disturbed soil carbon cycling, and altered greenhouse gas fluxes confirm that air pollution, climate regulation, and agricultural sustainability are interwoven issues. The protection of the shield function of the atmosphere and the mitigation of the agricultural "strangler" paradox are therefore imperative strategic needs.

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