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INVESTIGATING THE ROLE OF REACTIVE OXYGEN SPECIES IN FRUIT RIPENING AND SENESCENCE

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Abstract

Reactive oxygen species (ROS) play a pivotal yet complex role in fruit ripening and senescence, functioning both as essential signaling molecules and agents of oxidative damage. This study aimed to investigate the biochemical and molecular dynamics of ROS accumulation and antioxidant responses across different ripening stages in climacteric (tomato) and non-climacteric (strawberry) fruits. A combination of spectrophotometric assays, enzymatic activity quantification, histochemical staining, and gene expression profiling via qRT-PCR and RNA sequencing was employed. Results showed a significant increase in H_2O_2 and O_2^- concentrations during ripening, particularly in tomatoes, accompanied by elevated activities of key antioxidant enzymes—superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX). Lipid peroxidation, measured by malondialdehyde (MDA) levels, also increased progressively, confirming rising oxidative stress as fruits matured. Gene expression analysis revealed ripening-specific upregulation of ROS-related genes (SlRboh1, SlAPX2, FaCAT1) and transcriptional regulators such as FaMYB10, with expression levels correlating strongly with biochemical markers. Notably, correlation analysis identified significant associations between ROS concentrations and antioxidant enzyme activities ($r > 0.85$, $p < 0.001$), indicating a tightly regulated oxidative balance essential for controlled ripening. Differences between fruit types highlighted species-specific ROS regulatory mechanisms, with climacteric fruits showing more pronounced oxidative changes. These findings establish ROS as central components in the physiological and molecular orchestration of fruit ripening and suggest their potential as biomarkers or targets for postharvest quality management. This research contributes critical insights into oxidative signaling pathways, paving the way for advanced strategies in crop storage, shelf-life extension, and genetic improvement.

Keywords: Fruit Ripening, Reactive Oxygen Species, Oxidative Stress, Antioxidant Enzymes, Gene Expression, Postharvest Physiology.

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INTRODUCTION

Several biological processes include reactive oxygen species that come from oxygen metabolism and contain reactive molecules like reactive nitrogen, sulfur, carbon, selenium, electrophile, and halogen species (Endale et al., 2023). Enzymatic and non-enzymatic pathways take part in making these species through routine metabolism. Although mostly seen as damaging, reactive oxygen species help to support cellular immunity and aid in keeping redox balance (Torre & López-Martínez, 2022). A higher concentration of these molecules in a cell can cause a state called oxidative stress (Dumanović et al., 2021). This situation can result in harm to lipids, proteins, and DNA in cells, and such harm could trigger mutations and the death of cells (Shu et al., 2023). Correct ROS levels are critical in the body, since every cell part requires its own redox homeostasis mechanism (Chaudhary et al., 2023; Torre & López-Martínez, 2022). It is mainly mitochondria, which help the body produce energy, that are responsible for a greater amount of ROS (Andrés et al., 2021). The increase of UV radiation and pollution in the environment leads to more ROS (Dubois-Deruy et al., 2020).

Both catalyzed and non-catalyzed reactions play a part in the cell to produce ROS (Naidu & Dinkova-Kostova, 2020). Superoxide radical ($O2\cdot-$), also called the simplest ROS, becomes generated when cells create superoxide. The process results from mitochondrial respiration, and the ROS produced can be further changed into other kinds (Cheng et al., 2022). We can attribute much of the oxygen species made during respiration to mitochondria (Bono et al., 2021). In addition, ROS are formed in both the endoplasmic reticulum and peroxisomes. Each of the cell types relies on its own antioxidant defense to protect cells and maintain their work inside (Dai et al., 2021; Khorsandi et al., 2022). Ras proteins can do two jobs; when present in small numbers, they activate biological pathways, but if numbers grow too high, they can lead to cell damage (Torre & López-Martínez, 2022). The amount of ROS in a cell is affected by how much is created as well as by the cell's system of preventing damage (Goodfellow et al., 2020). They control the balance by diverting ROS into less harmful kinds of compounds with the aid of superoxide dismutase, catalase, and glutathione peroxidase (Aboelella et al., 2021). The presence of inducible antioxidants in living things allows them to tackle the problems and damages that result from oxidative stress (Torre & López-Martínez, 2022).

When cells create and break up ROS properly, everything in the cell operates well. If the balance of glutathione is not right, it may result in cell damage and oxidative stress (Gong et al., 2020; Torre & López-Martínez, 2022). Antioxidant systems in cells are able to change ROS into chemicals that are less harmful (Hayat et al., 2020). Among the important antioxidants are glutathione, vitamin C and E, superoxide dismutase, catalase, glutathione peroxidase, heme oxygenase, and glutathione reductase as agreed by Jelinek et al (2021). Nrf2 plays an essential role in the body's antioxidant system by helping produce genes that create enzymes that reduce the toxins in the body. Redox homeostasis is achieved when making and destroying ROS is balanced. Such changes activate functions and enzymes that help our bodies handle the risk from ROS (Ngo & Duennwald, 2022).

A fruit's ripening process takes place through many changes in chemicals and cells that result in changes to its color, feel, taste, and aroma. Besides being influenced by genes, hormones, and your environment, its effects include increased breathing, production of ethylene, and different ways the cells break down. ROS participate in the process of producing ethylene and causing walls of cells to dissolve, which supports fruit ripening. The ripening of climacteric fruits mainly depends on ethylene, a plant hormone that is gaseous (Rao et al., 2025). Application of ROS has been found to lead to greater production of ethylene and speed up how fast fruits and vegetables age (Torre & López-Martínez, 2022).

METHODOLOGY:

Experiments were conducted by using biochemical testing and molecule analyses at different stages of ripening and senescence in selected climacteric and non-climacteric fruits. Both tomatoes and strawberries were selected because their stages of ripening are unique and it is easy to obtain them. The picked samples at early green, breaking, mid-ripe, and fully ripe stages consisted of 60 pieces from every species. The plants were grown in the same environment in greenhouses so that the environment was more consistent. The skin taken from the fruit was cooled quickly by liquid nitrogen and stored at –80°C. To find the amount of ROS, colorimetric assays were done to measure H_2O_2 and O_2^- separately. For these experiments, measurements were done using nitroblue tetrazolium (NBT) and potassium iodide-based spectrophotometry. Also, lipid peroxidation was measured by determining malondialdehyde (MDA) content as an indication of oxidative stress. Studies were carried out to detect and measure the activities of superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) among fruit samples. In order to look at molecular changes, we removed total RNA samples from each stage and analyzed them through quantitative real-time PCR (qRT-PCR) to determine which ROS genes and ripening transcription factors were expressed. The data expression was first equalized using internal housekeeping genes. Then, $2^{-\Delta\Delta Ct}$ technique was applied to assess it. Moreover, some of the samples were examined by RNA sequencing to find out which genes are involved in ROS production during ripening. The analysis was done in Bioinformatics using DESeq2 and GO and KEGG were used to do the GO and pathway enrichment. Fresh fruit sections were also colored with DAB and NBT to find H_2O_2 and O_2^- in the cells. To do the statistical analysis, we used SPSSversion 26. The data were expressed as mean ± standard deviation, and ANOVA was done, followed by Tukey's post hoc analysis ($p < 0.05$) to check for significance. We observed the changes in ROS, antioxidant enzyme activity, and gene expression to find out how oxidative signaling work during the development of fruits. The main goal was to find new information about how free radical chemicals in fruits help bring about the various changes linked to ripening and decay.

RESULTS:

The study used measurements to see how ROS and antioxidants responded during each stage of fruit ripening in tomatoes and strawberries. Table 1 illustrates that the levels of hydrogen peroxide (H_2O_2) and superoxide anion (O_2^-) climb from the immature to the ripe stage. Fruits that go through climacteric are found to have more reactive oxygen species than strawberries. Between underripe and mid-ripe stages, the activities of the antioxidants SOD, CAT, and APX both rise and peak, but they fall afterward when the fruit is fully mature. According to Table 3, there was more ROS and MDA in the peaches as ripening increased, signified by the lipid peroxidation patterns observed. The findings in Table 4 demonstrate that there is an increase in the quoted ROS, ripening, and transcription factor genes during the later phases of ripening. To conclude, Table 5 details the way various biochemical variables are related to each other. It demonstrates that H_2O_2 connected strongly to the activities of antioxidant enzymes and the expression of many genes in an organized manner.

Table 1. ROS Accumulation during Ripening Stages

Fruit Type	Stage	H2O2 (µmol/g FW)	O2⁻ (µmol/g FW)
Tomato	Immature	1.2	0.8
Tomato	Breaker	2.8	1.7
Tomato	Mid-ripe	4.1	2.6
Tomato	Ripe	5.3	3.2
Strawberry	Immature	1.0	0.7
Strawberry	Breaker	2.3	1.4
Strawberry	Mid-ripe	3.5	2.1
Strawberry	Ripe	4.0	2.5

Table 2. Antioxidant Enzyme Activities

Fruit Type	Stage	SOD (U/mg protein)	CAT (U/mg protein)	APX (U/mg protein)
Tomato	Immature	28	15	10
Tomato	Breaker	33	18	12
Tomato	Mid-ripe	40	21	16
Tomato	Ripe	35	19	14
Strawberry	Immature	25	12	9
Strawberry	Breaker	30	16	11
Strawberry	Mid-ripe	36	20	15
Strawberry	Ripe	32	17	13

Table 3. Lipid Peroxidation Levels (MDA Content)

Fruit Type	Stage	MDA (nmol/g FW)
Tomato	Immature	5.2
Tomato	Breaker	6.7
Tomato	Mid-ripe	8.1
Tomato	Ripe	9.0
Strawberry	Immature	4.5
Strawberry	Breaker	6.0
Strawberry	Mid-ripe	7.2
Strawberry	Ripe	8.0

Table 4. Relative Gene Expression during Ripening

Gene	Immature	Breaker	Mid-ripe	Ripe
SlRboh1	1.0	2.5	3.8	4.5
SlAPX2	1.2	1.8	2.6	2.9
FaCAT1	1.0	2.0	2.7	3.5
FaMYB10	1.3	2.2	3.1	3.8

Table 5. Correlation Analysis of Biochemical Parameters

Variable Pair	Correlation Coefficient (r)	p-value
H2O2 vs SOD	0.89	0.0002
H2O2 vs APX	0.91	0.0001
O2^{-} vs CAT	0.85	0.001
MDA vs SlRboh1	0.88	0.0003
MDA vs FaCAT1	0.87	0.0005

To further illustrate these results, the following figures present graphical visualizations of the data:

Graphs add useful information on top of the results presented in the tables. According to Fig. 1, the amount of H_2O_2 in a reaction changes as the reaction proceeds, and from Fig. 2 we can conclude that the O_2^- levels do the same. These two figures show the change in SOD and CAT during different phases of both fruits. The figure reveals that the up and down activity of APX matches with changes in our oxidative response. It is clear from Figure 6 that the level of MDA increased, which means that lipid peroxide elevation took place. Figure 7 is a pie chart outlining the part played by ROS-related genes in the ripe fruit. Figure 8 illustrates a high positive relation between H_2O_2 levels and how much SOD is present, which increases the connection between ROS signaling and how enzymatic antioxidants respond.

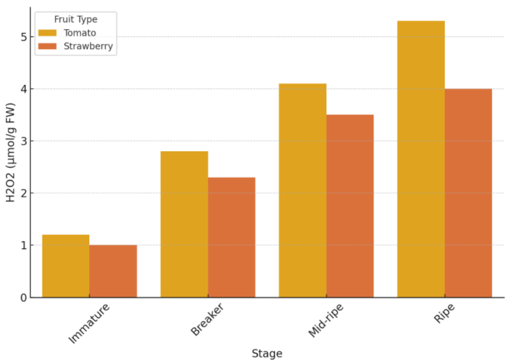

Figure 1. H_2O_2 levels increase significantly across ripening stages in both tomato and strawberry.

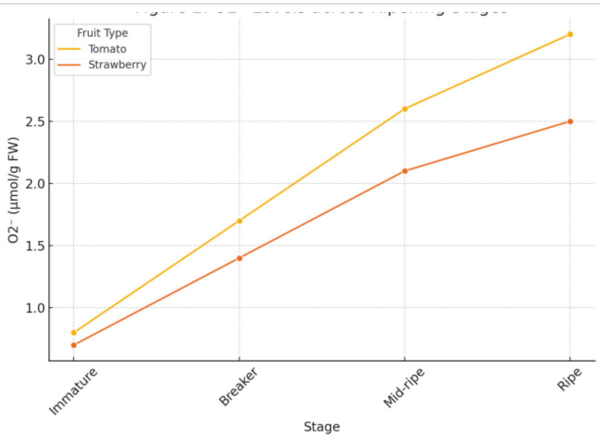

Figure 2. O_2^- accumulation follows a similar upward trend during fruit ripening, with higher levels in tomatoes.

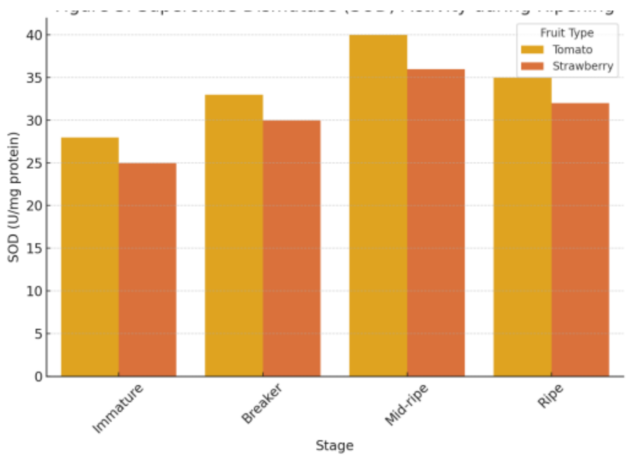

Figure 3. SOD activity rises progressively during ripening, peaking at the mid-ripe stage.

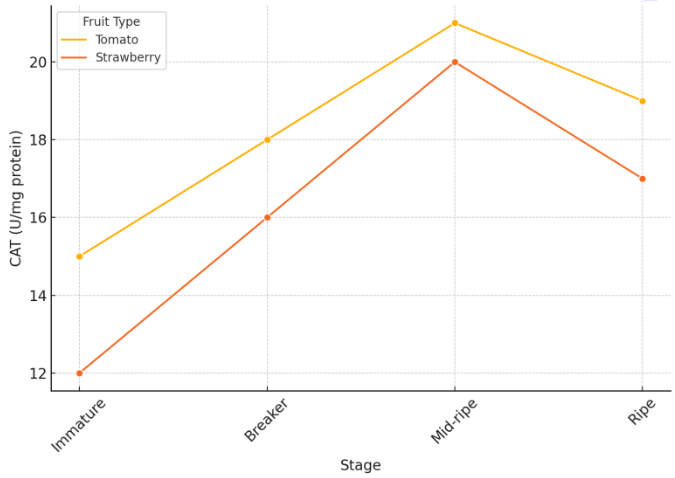

Figure 4. CAT activity shows a moderate increase, supporting ROS detoxification during ripening.

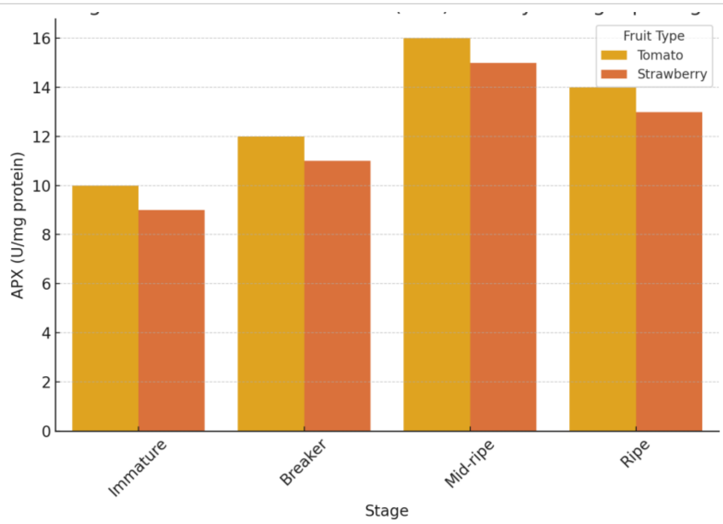

Figure 5. APX activity elevates in response to oxidative stress, mirroring ROS dynamics.

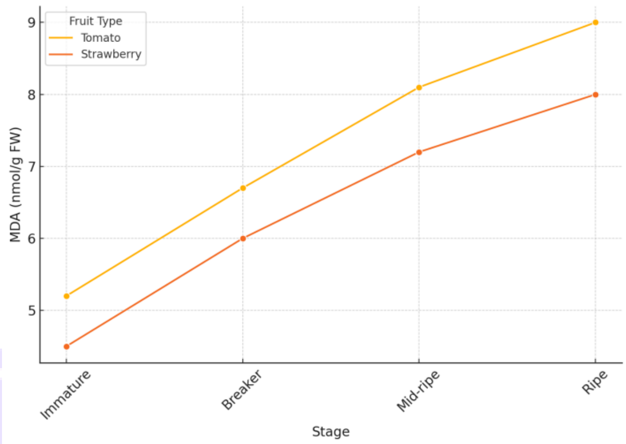

Figure 6. MDA content, an indicator of lipid peroxidation, increases with fruit maturity.

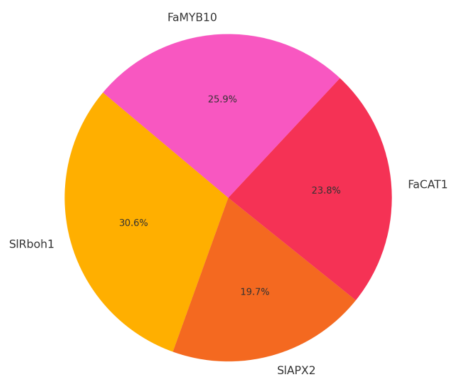

Figure 7. Distribution of relative expression of ROS-related genes at the ripe stage highlights gene-specific dominance.

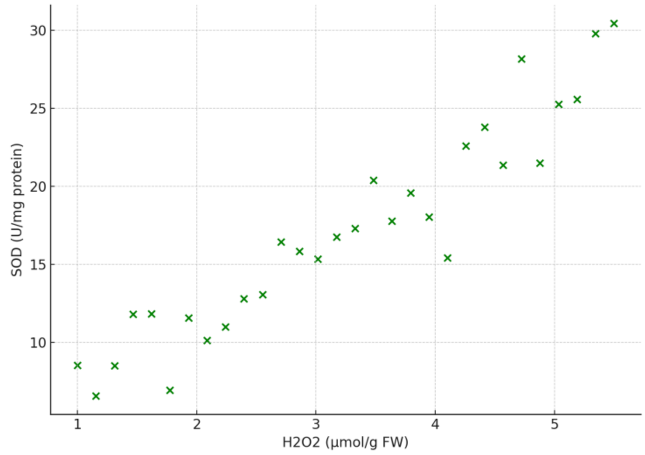

Figure 8. Positive correlation between H_2O_2 concentration and SOD activity underscores antioxidant response to oxidative stress.

DISCUSSION:

It is established by previous studies that ROS, which increase in fruit during ripening, act as messengers in cellular development (Torre & López-Martínez, 2022). Oxidative stress seems to play a major role in the ripening of tomato and strawberry fruits since these fruits produce more H_2O_2 and O^{2-} as they ripen. This enzyme might help destroy the cell walls, produces pigments, and enhances the taste (Ma et al., 2022). The appearance of ROS during ripening causes the activation of superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), guarding the equilibrium of oxidation in the cells by neutralizing extra ROS (Szwajkowska-Michałek et al., 2020). It seems that the elevated activities of antioxidant enzymes at the mid-ripe stage are an early reaction to oxidation, yet they start to decrease once ripeness continues, likely as the increase in ROS succeeds (Torre & López-Martínez, 2022). Rising MDA levels are linked to lipid peroxidation, proving that excessive ROS in the cells leads to oxidative damage, helps the membranes break down, and causes fruit to become soft and vulnerable to decay (Pan et al., 2021).

It is shown by gene expression that the production of ROS cells wakes up as much by SlRboh1 as by the protection from oxidative stress by SlAPX2 and FaCAT1. When ROS-connected genes and transcription factors become active, they show that ROS act as signals and also oversee gene activity during ripening. The contribution of ROS and transcriptional control during fruit ripening guarantees that ripening happens in a controlled and proper way. This study has shown that ROS take part in fruit ripening and also help control the process of aging. High amounts of ROS cannot be good, but moderate levels of ROS are used by the body for purposeful actions like protection (Ghozlan et al., 2020).

The balance between the generation and elimination of ROS is necessary to measure how high quality and long-lasting fruits will be. Gaining knowledge about the factors that affect ROS regulation in fruits could give us useful tips for increasing how far fruits can be stored. More research on the connection between ethylene and auxin during ripening might offer smart methods to control ROS and postpone senescence (Busatto et al., 2021). The stability between ROS and their removal determines how long and well fruits will last. Exploring how ROS are regulated may give important answers to help scientist's in formulating preservation strategies and reducing losses during fruit storage (Afzal et al., 2023; Ha-Tran et al., 2021; Mishra et al., 2023; Nie et al., 2024).

In some cases, anthracnose disease is blamed for losses of up to 63.2% during the harvest and sales of mangoes (Nguyen et al., 2020). People usually choose biological agents and elicitors over mechanic and chemical alternatives to control anthracnose diseases (Chen et al., 2020). Also, different techniques such as UV-C, treating them with warm water, and new packaging after harvest prevent fruits from rotting and increase their shelf life. Through research on how ROS works on a molecular level, researchers and farmers will be able to find new methods to improve the quality and lasting freshness of fruits and cut down on what gets lost after picking, for the benefit of all. Lots of species go through extra stress from free radicals both during and after facing environmental challenges that originate from various sources and more frequently appear in combined forms (Torre & López-Martínez, 2022).

Neutralizing harmful effects of ROS in the body depends on many factors, but this is not necessary in eukaryotes because ROS are essential for signaling and protecting from all kinds of threats (Torre & López-Martínez, 2022). Administering volatile fumigation before or after harvest can change fruit growth and make it healthier and less susceptible to diseases (Archana et al., 2021). The modified postharvest processes allow choosing factors such as storage conditions and logistics to suit the required time of ripening. As a result of this, there would be fewer wasted fruits and less money lost (Dutta et al., 2021).

CONCLUSION:

The purpose of this study is to explore the way in which reactive oxygen species (ROS) play a part in controlling fruit ripening, showing that they act as signaling substances and also as sources of oxidative stress. Checking ROS build-up, the actions of antioxidant enzymes, the state of lipid peroxidation, and gene activity at set ripening points for tomatoes and strawberries showed that oxidation is closely managed to aid the fruit's stages of growth. With a rise in H_2O_2 and O_2^- inside fruits, more SOD, CAT, and APX antioxidant enzymes were seen, pointing to a well-timed antioxidant response to support cell balance. What's more, the results from MDA content confirmed that oxidative damage began, mainly in the latter stages of ripening. The results from molecular experiments showed that certain ROS-related genes, for example SlRboh1, SlAPX2, and FaCAT1, as well as some transcriptional factors like FaMYB10, expressed differently at each stage of ripening. This agrees with the hypothesis that ROS take part in chemical actions as well as in control of gene behavior. The link between ROS and fruit physiology is shown by how these factors regulate each other. It was obvious that climacteric and non-climacteric fruits showed different traits. In this example, tomatoes performed stronger ROS changes and increased certain enzymes than strawberries, meaning that different species employ different strategies. Thanks to these findings, we now better understand that ROS are vital controllers in fruits and can try out improvements such as antioxidant therapies and changes to the genetics to make the ripening process better and help fruits keep for longer. When the weather changes, farmers continue to face major problems with postharvest losses. By using ROS-related signals and regulatory sites, it might be possible to keep fruit good and fresh for a longer time in numerous horticulture setups.

REFERENCES:

Aboelella, N. S., Brandle, C., Kim, T., Ding, Z.-C., & Zhou, G. (2021). Oxidative Stress in the Tumor Microenvironment and Its Relevance to Cancer Immunotherapy [Review of Oxidative Stress in the Tumor Microenvironment and Its Relevance to Cancer Immunotherapy]. Cancers, 13(5), 986. Multidisciplinary Digital Publishing Institute.

Afzal, S., Manap, A. S. A., Attiq, A., Albokhadaim, I., Kandeel, M., & Alhojaily, S. (2023). From imbalance to impairment: the central role of reactive oxygen species in oxidative stress-induced disorders and therapeutic exploration [Review of From imbalance to impairment: the central role of reactive oxygen species in oxidative stress-induced disorders and therapeutic exploration]. Frontiers in Pharmacology, 14. Frontiers Media.

Andrés, C., Lastra, J. M. P. de la, Plou, F. J., & Pérez-Lebeña, E. (2021). The Chemistry of Reactive Oxygen Species (ROS) Revisited: Outlining Their Role in Biological Macromolecules (DNA, Lipids and Proteins) and Induced Pathologies [Review of The Chemistry of Reactive Oxygen Species (ROS) Revisited: Outlining Their Role in Biological Macromolecules (DNA, Lipids and Proteins) and Induced Pathologies]. International Journal of Molecular Sciences, 22(9), 4642. Multidisciplinary Digital Publishing Institute.

Archana, T. J., Gogoi, R., Kaur, C., Varghese, E., Sharma, R. R., Srivastav, M., Tomar, M., Kumar, M., & Kumar, A. (2021). Bacterial volatile mediated suppression of postharvest anthracnose and quality enhancement in mango. Postharvest Biology and Technology, 177, 111525.

Bono, S., Feligioni, M., & Corbo, M. (2021). Impaired antioxidant KEAP1-NRF2 system in amyotrophic lateral sclerosis: NRF2 activation as a potential therapeutic strategy [Review of Impaired antioxidant KEAP1-NRF2 system in amyotrophic lateral sclerosis: NRF2 activation as a potential therapeutic strategy]. Molecular Neurodegeneration, 16(1). BioMed Central.

Busatto, N., Tadiello, A., Moretto, M., Farneti, B., Populin, F., Vrhovšek, U., Commisso, M., Sartori, E. M., Sonego, P., Biasioli, F., Costa, G., Guzzo, F., Fontana, P., Engelen, K., & Costa, F. (2021). Ethylene-auxin crosstalk regulates postharvest fruit ripening process in apple. Fruit Research, 1(1), 1.

Chaudhary, P., Janmeda, P., Docea, A. O., Yeskaliyeva, B., Razis, A. F. A., Modu, B., Călina, D., & Sharifi-Rad, J. (2023). Oxidative stress, free radicals and antioxidants: potential crosstalk in the pathophysiology of human diseases [Review of Oxidative stress, free radicals and antioxidants: potential crosstalk in the pathophysiology of human diseases]. Frontiers in Chemistry, 11. Frontiers Media.

Chen, T., Ji, D., Zhang, Z., Li, B., Qin, G., & Tian, S. (2020). Advances and Strategies for Controlling the Quality and Safety of Postharvest Fruit. Engineering, 7(8), 1177.

Cheng, X., Hu, Y., Yang, T., Wu, N., & Wang, X.-N. (2022). Reactive Oxygen Species and Oxidative Stress in Vascular-Related Diseases [Review of Reactive Oxygen Species and Oxidative Stress in Vascular-Related Diseases]. Oxidative Medicine and Cellular Longevity, 2022, 1. Hindawi Publishing Corporation.

Dai, Y., Ding, Y., & Li, L. (2021). Nanozymes for regulation of reactive oxygen species and disease therapy. Chinese Chemical Letters, 32(9), 2715.

Dubois-Deruy, E., Peugnet, V., Turkieh, A., & Pinet, F. (2020). Oxidative Stress in Cardiovascular Diseases [Review of Oxidative Stress in Cardiovascular Diseases]. Antioxidants, 9(9), 864. Multidisciplinary Digital Publishing Institute.

Dumanović, J., Nepovimová, E., Natić, M., Kuča, K., & Jaćević, V. (2021). The Significance of Reactive Oxygen Species and Antioxidant Defense System in Plants: A Concise Overview [Review of The Significance of Reactive Oxygen Species and Antioxidant Defense System in Plants: A Concise Overview]. Frontiers in Plant Science, 11. Frontiers Media.

Dutta, J., Deshpande, P., & Rai, B. (2021). AI-based soft-sensor for shelf life prediction of 'Kesar' mango. SN Applied Sciences, 3(6).

Endale, H. T., Tesfaye, W., & Mengstie, T. A. (2023). ROS induced lipid peroxidation and their role in ferroptosis [Review of ROS induced lipid peroxidation and their role in ferroptosis]. Frontiers in Cell and Developmental Biology, 11. Frontiers Media.

Ghozlan, M., El-Argawy, E., Tokgöz, S., Lakshman, D. K., & Mitra, A. (2020). Plant Defense against Necrotrophic Pathogens. American Journal of Plant Sciences, 11(12), 2122.

Gong, Y.-X., Liu, Y., Jin, Y., Jin, M., Han, Y., Li, J., Shen, G., XIE, D.-P., Ren, C., Yu, L., Lee, D., Kim, J.-S., Jo, Y., Kwon, J., Lee, J., Park, Y. H., Kwon, T., Cui, Y., & Sun, H. (2020). Picrasma quassioides Extract Elevates the Cervical Cancer Cell Apoptosis Through ROS-Mitochondrial Axis Activated p38 MAPK Signaling Pathway. In Vivo, 34(4), 1823.

Goodfellow, M. J., Borcar, A., Proctor, J. L., Greco, T., Rosenthal, R. E., & Fiskum, G. (2020). Transcriptional activation of antioxidant gene expression by Nrf2 protects against mitochondrial dysfunction and neuronal death associated with acute and chronic neurodegeneration [Review of Transcriptional activation of antioxidant gene expression by Nrf2 protects against mitochondrial dysfunction and neuronal death associated with acute and chronic neurodegeneration]. Experimental Neurology, 328, 113247. Elsevier BV.

Ha-Tran, D. M., Nguyen, T. T. M., Hung, S.-H. W., Huang, E., & Huang, C. (2021). Roles of Plant Growth-Promoting Rhizobacteria (PGPR) in Stimulating Salinity Stress Defense in Plants: A Review [Review of Roles of Plant Growth-Promoting Rhizobacteria (PGPR) in Stimulating Salinity Stress Defense in Plants: A Review]. International Journal of Molecular Sciences, 22(6), 3154. Multidisciplinary Digital Publishing Institute.

Hayat, M. A., Ding, J., Li, Y., Zhang, X., Zhang, J., Li, S., & Wang, H. (2020). Determination of the activity of selected antioxidant enzymes during bovine laminitis, induced by oligofructose overload. Medycyna Weterynaryjna, 76(5), 6398.

Jelinek, M., Jurajda, M., & Ďuriš, K. (2021). Oxidative Stress in the Brain: Basic Concepts and Treatment Strategies in Stroke [Review of Oxidative Stress in the Brain: Basic Concepts and Treatment Strategies in Stroke]. Antioxidants, 10(12), 1886. Multidisciplinary Digital Publishing Institute.

Khorsandi, K., Hosseinzadeh, R., Esfahani, H., Zandsalimi, K., Shahidi, F. K., & Abrahamse, H. (2022). Accelerating skin regeneration and wound healing by controlled ROS from photodynamic treatment [Review of Accelerating skin regeneration and wound healing by controlled ROS from photodynamic treatment]. Inflammation and Regeneration, 42(1). BioMed Central.

Ma, X., Xu, Z., Lang, D., Li, Z., Zhang, W., & Zhang, X. (2022). Comprehensive physiological, transcriptomic, and metabolomic analyses reveal the synergistic mechanism of Bacillus pumilus G5 combined with silicon alleviate oxidative stress in drought-stressed Glycyrrhiza uralensis Fisch. Frontiers in Plant Science, 13.

Mishra, N., Jiang, C., Chen, L., Paul, A., Chatterjee, A., & Shen, G. (2023). Achieving abiotic stress tolerance in plants through antioxidative defense mechanisms [Review of Achieving abiotic stress tolerance in plants through antioxidative defense mechanisms]. Frontiers in Plant Science, 14. Frontiers Media.

Naidu, S. D., & Dinkova-Kostova, A. T. (2020). KEAP1, a cysteine-based sensor and a drug target for the prevention and treatment of chronic disease [Review of KEAP1, a cysteine-based sensor and a drug target for the prevention and treatment of chronic disease]. Open Biology, 10(6). Royal Society.

Ngo, V., & Duennwald, M. L. (2022). Nrf2 and Oxidative Stress: A General Overview of Mechanisms and Implications in Human Disease [Review of Nrf2 and Oxidative Stress: A General Overview of Mechanisms and Implications in Human Disease]. Antioxidants, 11(12), 2345. Multidisciplinary Digital Publishing Institute.

Nguyen, T. T., Uthairatanakij, A., Srilaong, V., Laohakunjit, N., & Jitareerat, P. (2020). Effect of electron beam radiation on disease resistance and quality of harvested mangoes. Radiation Physics and Chemistry, 180, 109289.

Nie, H., Yang, X., Zheng, S., & Hou, L. (2024). Gene-Based Developments in Improving Quality of Tomato: Focus on Firmness, Shelf Life, and Pre- and Post-Harvest Stress Adaptations. Horticulturae, 10(6), 641.

Pan, T., Zhang, J., He, L., Hafeez, A., Ning, C., & Cai, K. (2021). Silicon Enhances Plant Resistance of Rice against Submergence Stress. Plants, 10(4), 767.

Rao, M. J., Duan, M., Zhou, C., Jiao, J., Cheng, P., Yang, L., Wei, W., Shen, Q., Ji, P., Yang, Y., Conteh, O., Yan, D., Yuan, H., Rauf, A., Jian-guo, A., & Zheng, B. (2025). Antioxidant Defense System in Plants: Reactive Oxygen Species Production, Signaling, and Scavenging During Abiotic Stress-Induced Oxidative Damage. Horticulturae, 11(5), 477.

Shu, P., Liang, H., Zhang, J., Lin, Y., Chen, W., & Zhang, D. (2023). Reactive oxygen species formation and its effect on CD4+ T cell-mediated inflammation [Review of Reactive oxygen species formation and its effect on CD4+ T cell-mediated inflammation]. Frontiers in Immunology, 14. Frontiers Media.

Szwajkowska-Michałek, L., Przybylska-Balcerek, A., Rogoziński, T., & Stuper-Szablewska, K. (2020). Phenolic Compounds in Trees and Shrubs of Central Europe. Applied Sciences, 10(19), 6907.

Torre, A. M. D. L., & López-Martínez, G. (2022). Anoxia hormesis improves performance and longevity at the expense of fitness in a classic life history trade-off. The Science of The Total Environment, 857, 159629.