

# [Harnessing evolutionary toxins for signaling: reactive oxygen species, nitric oxi...](https://assignbuster.com/harnessing-evolutionary-toxins-for-signaling-reactive-oxygen-species-nitric-oxide-and-hydrogen-sulfide-in-plant-cell-regulation/)

[](https://assignbuster.com/)[Health & Medicine](https://assignbuster.com/essay-subjects/health-n-medicine/)

## Introduction

Reactive compounds such as those derived from oxygen, nitrogen, and sulfur are instrumental in cell signaling pathways ( [Mittler et al., 2011](#B46) ; [Mur et al., 2013](#B48) ; [García-Mata and Lamattina, 2013](#B17) ; [Hancock and Whiteman, 2014](#B22) ). It appears that they have effects in a wide range of organisms from simple prokaryotes to humans and higher plants. However, despite the fact that organisms are using such compounds in a positive way, this use belies their inherent toxic nature. It appears therefore that during evolution cells have had to tolerate the presence of such compounds and have over time adopted them for their own gains.

The atmosphere during the history of the Earth has not been unchanging. Four billion years ago the atmosphere would have been approximately one part per million oxygen ( [Lane, 2002](#B33) ) and yet today many organisms easily survive in 21% oxygen (over 200, 000 parts per million). Approximately two and half billion years ago oxygen would have started to increase due to biological activity ( [Lyons et al., 2014](#B40) ). It would not have been a sudden rise but as organisms evolved they had a new toxin to contend with. Oxygen is a di-radical ( [Cheeseman and Slater, 1993](#B9) ) and undergoes redox reactions to yield a family of reactive compounds [the so called reactive oxygen species (ROS)], including the superoxide anion, hydrogen peroxide (H 2 O 2 ) and the hydroxyl radical. The issue for newly evolving organisms as oxygen levels rose was that many of the ROS are toxic ( [Wallace and Melov, 1998](#B67) ; [Halliwell and Gutteridge, 2015](#B19) ). Therefore to counter this organisms have evolved a wide range of antioxidant defenses, which prevents the build-up of ROS and limits the damage that may be done ( [Blokhina et al., 2003](#B4) ). These include enzymes such as superoxide dismutase (SOD) and catalase, as well as small compounds such as ascorbate and glutathione (GSH). Manipulation of these, such as levels of SOD, has been shown to increase life span in some species ( [Parkes et al., 1998](#B55) ) showing that the control of ROS levels is crucially important. Furthermore, in a treatise on glutathione levels [Schafer and Buettner (2001)](#B60) discussed the importance of the maintenance of intracellular redox status – it must be kept much reduced – and how oxidation can lead to either apoptosis or necrosis. However, despite all this, cells still use ROS as signaling molecules ( [Mittler et al., 2011](#B46) ). It appears that the presence of oxygen in the atmosphere has had a profound influence in the evolution of aerobic organisms, as has been discussed by others ( [Lane, 2002](#B33) ; [Dowling and Simmons, 2009](#B15) ; [Metcalfe and Alonso-Alvarez, 2010](#B43) ). During such evolution cells have not just learnt to tolerate the presence of oxygen and its downstream products, but have harnessed such products for a positive action; both in and between cells.

Similar tolerance of toxic compounds can be seen with nitrogen- and sulfur-based compounds. The most commonly studied compound here is nitric oxide (NO). This was found to be instrumental in the control of vascular tone in mammals, where it was originally known as endothelial-derived relaxing factor (EDRF: [Palmer et al., 1987](#B53) ) but has since been found to be a key part of cell signaling in a range of organisms including plants. Exposure of plants to NO can be from natural sources such as the soil ( [Davidson, 1991](#B11) ; [Skiba et al., 1993](#B64) ; [Ludwig et al., 2001](#B39) ). Plants also have the capacity to make intracellular NO (reviewed by [Mur et al., 2013](#B48) ). However, NO is inherently toxic, and for animals diet may help here, showing that plants cells have compounds which mitigate against the harmful effects of this compound ( [Paquay et al., 2000](#B54) ). Peroxynitrite, derived from the reaction of NO with ROS is also toxic ( [Bartosz, 1996](#B3) ) but it is also known to be involved in signaling ( [Klotz, 2005](#B31) ).

Evolution has also been shaped by the presence of hydrogen sulfide (H 2 S). H 2 S is produced at thermal vents ( [Martin et al., 2008](#B41) ), where many organisms still rely on the presence of sulfur compounds as a source of reducing power. While many organisms have adapted to life in the presence of H 2 S ( [Tobler et al., 2016](#B66) ), such as fish in H 2 S-rich springs ( [Kelley et al., 2016](#B30) ), clearly life also has left such niche environments. Therefore during evolution species have developed, some remaining in the presence of, and tolerating, H 2 S while others has escaped it into an oxygen-rich environment. H 2 S is, like other reactive compounds considered here, very toxic. It is known, for example, that H 2 S is an inhibitor of mitochondrial electron transport chains (Complex IV) and so inhibits ATP production ( [Dorman et al., 2002](#B14) ). It is so toxic that it was used as a chemical weapon ( [Szinicz, 2005](#B65) ), yet organisms have harnessed it as a signaling molecule. It has shaped events in evolution and been adopted as part of metabolism ( [Olson and Strub, 2015](#B51) ). Bacteria are known to produce H 2 S ( [Clarke, 1953](#B10) ), in plants H 2 S is used in sulfur metabolism ( [Calderwood and Kopriva, 2014](#B8) ), whilst at very low concentrations in animals instead of inhibiting the electron transport chain of mitochondria it has been shown to be a source of reducing power for the production of ATP ( [Bouillaud et al., 2013](#B5) ). Here is a good example of how organisms have evolved in the presence of a toxic compound but adapted to use it for positive reasons.

The majority of the literature regarding the signaling by reactive compounds concentrates on ROS, NO, and most recently H 2 S. However, the early atmosphere of the Earth’s history was also rich in other noxious compounds, such as methane, ammonia, and hydrogen ( [Lane, 2002](#B33) ). Such compounds should also be included in the suite of potential cell signaling molecules, giving a more holistic understanding of how all these compounds may be controlling cellular functions in plants.

### Roles of Reactive Signaling Compounds

Signaling in cells involves a myriad of different components, some of which are small transient molecules. When a molecule has been proposed as a signaling component there are certain criteria that may be looked for. It should be made where and when needed, be recognized as being present (so it may transmit a specific message), be able to move the message to a new position in the cell (or to another cell), and be removed when no longer needed ( [Hancock, 2016](#B20) ). Looking at ROS, NO, and H 2 S it can be argued that such criteria are met.

Enzymes are involved in the generation of reactive signals. As such proteins are often only active when required and usually have defined subcellular locations, the reactive molecules produced are only present where and when needed. ROS are generated from the NADPH oxidase family of enzymes, but enzymes such as peroxidases may also contribute to ROS production. There is some controversy about the production of NO in plants. There is almost certainly no nitric oxide synthase (NOS) in higher plants ( [Jeandroz et al., 2016](#B28) ) but plants can generate NO from other enzymes such as nitrate reductase ( [Rockel et al., 2002](#B58) ). H 2 S can be generated by desulfhydrases in plants ( [Alvarez et al., 2010](#B1) ). Removal of ROS will be through antioxidants whilst NO will react with thiols, metals or be oxidized. H 2 S can be removed through the action of *O* -acetylserine (thiol) lyase ( [Youssefian et al., 1993](#B70) ).

ROS, NO, and H 2 S are all diffusible so they are all able to move their message through, or between, the cells. However, some care is needed when discussing if membranes can be traversed. For example, NO can be a radical and uncharged but the loss or gain of an electron will yield NO + and NO - ; both are hydrophilic. In a similar manner, the ROS H 2 O 2 is neutral and can move across the lipid bilayer but O 2 •– would not, unless protonated. Furthermore, it must be considered that such compounds can react with the membranes themselves, leading to lipid peroxidation or the formation of nitro-lipids. The formation of nitro-fatty acids has been suggested to be important for further signaling ( [Mata-Pérez et al., 2016](#B42) ).

It can be seen, therefore, that ROS, NO, and H 2 S can partake in signaling, that is, so long as their concentrations do not rise to toxic levels. One of the common themes of their use in plants is in response to stress ( [Misra et al., 2011](#B45) ; [Petrov and Van Breusegem, 2012](#B56) ; [Hancock and Whiteman, 2014](#B22) ). The list of stresses investigated in plants in which such signaling is implicated is wide ranging and includes: water stress; salt stress; pathogen challenge; heat/cold stress; metal ion (for example cadmium, copper, aluminum) stress. Under stress conditions the production of ROS etc is increased and this often impacts on the expression of antioxidant systems. However, ROS, NO, and H 2 S are also involved in normal plant development and function, such as: germination ( [Dooley et al., 2013](#B13) ); root development ( [Osuna et al., 2015](#B52) ); stomatal closure ( [Lisjak et al., 2010](#B37) ; [Murata et al., 2015](#B49) ); flower senescence ( [Zhang et al., 2011](#B72) ).

In order for ROS, NO, and H 2 S to be involved in signaling, once they are produced their presence has to be perceived for the message transduction to continue. With NO, the classical pathway determined in animals is the activation of the enzyme guanylyl cyclase and the resultant increase in cytosolic cGMP concentrations. Similar pathways have been studied in plants ( [Gross and Durner, 2016](#B18) ). However, one of the main mechanisms by which these reactive compounds participate in signaling is through the modification of the thiol groups of proteins. Thiol groups can be oxidized, as was seen with glyceraldehyde 3-phosphate dehydrogenase (GAPDH: [Hancock et al., 2005](#B21) ), nitrosated ( [Lindermayr et al., 2005](#B36) ) or *S* -sulfhydrated ( [Sen et al., 2012](#B62) ; [Romero et al., 2013](#B59) ). In each case the thiol group will be covalently modified in a reversible manner (although some modifications such as the formation of the sulphonic acid group seems to be irreversible), in such a way that the protein may have an altered function, as would be needed for signaling. This is akin to phosphorylation/dephosphorylation. Therefore, through such actions the signal can be transduced to the next component of the pathway leading to the appropriate cellular response.

### Interactions of Reactive Signaling Compounds

It is wrong to think about ROS, NO, and H 2 S working in isolation from each other. As mentioned above, reactions can take place between them. Superoxide anions and NO can react to form peroxynitrite, a possible signaling molecule ( [Klotz, 2005](#B31) ). NO and H 2 S can react to create nitrothiols, again with signaling potential ( [Whiteman et al., 2006](#B69) ), whilst ROS and H 2 S can also create downstream products ( [Li and Lancaster, 2013](#B35) ). It is known that NO and H 2 S can affect antioxidant levels in cells, and so influence ROS signaling. For example H 2 S will increase glutathione generation ( [De Kok et al., 1985](#B12) ), while others report alterations in ascorbate and antioxidant-related enzymes following H 2 S treatment ( [Shan et al., 2011](#B63) ). On the other hand, the activity of glucose-6-phosphate dehydrogenase (G6PDH) was increased following H 2 S treatment, which may increase ROS accumulation ( [Li et al., 2013](#B34) ). Therefore there will be interplay between such signaling molecules ( [Hancock and Whiteman, 2014](#B22) , [2015](#B23) ). Either they can influence each other’s generation, or they can scavenge each other, lowering the intracellular concentrations to reduce, or nullify, their effects.

As discussed above, thiols can be modified by this suite of reactive signaling molecules but of course they may be in direct competition with each other. Some proteins, such as GAPDH are known to be modified by both ROS and NO ( [Hancock et al., 2005](#B21) ), and this will not be the only competitive target. Furthermore, other convergence points may exist. It is known, for example, that the activity of MAP kinases are influenced by both ROS and NO ( [Kovtun et al., 2000](#B32) ; [Wang et al., 2010](#B68) ) and it would be no surprise to find H 2 S having a similar effect.

## Conclusion and Future Directions

It is clear therefore that during evolution certain molecules to which organisms have been exposed have not simply been tolerated but that they have been adopted as part of the suite of chemicals used for signaling. The most studied of these are ROS such as hydrogen peroxide ( [Mittler et al., 2011](#B46) ), NO ( [Mur et al., 2013](#B48) ), and H 2 S ( [Hancock and Whiteman, 2014](#B22) ). It may be that as such molecules had to be removed low levels always remained, while removal processes automatically gave cells a way to reverse cell signaling processes involving these compounds. What is clear is that carefully controlling the intracellular, and in some cases extracellular, concentrations of these reactive molecules are crucial for cell survival. Too much and crucial enzymes are inhibited, such as cytochrome oxidase ( [Dorman et al., 2002](#B14) ), or cellular damage ensues such as lipid peroxidation and DNA damage ( [Jena, 2012](#B29) ). Fluctuate the concentrations within defined limits and signaling can safely take place. Compartmentalisation is important here and may be part of the key to understanding how these signaling systems work without causing intolerable damage.

Besides ROS, NO, and H 2 S the early atmosphere of the Earth contained other small relatively reactive compounds. Amongst these are ammonia, methane and hydrogen ( [Lane, 2002](#B33) ). Therefore it is possible that as cells had to tolerate these too, that they also have been harnessed as signaling molecules.

It is known that nitrogen reduction, for example to ammonia, was involved in the development of the atmosphere ( [Brandes et al., 1998](#B6) ). Ammonia has been shown to have effects in biological systems, amongst which is its toxicity ( [Britto and Kronzucker, 2002](#B7) ). Plants are exposed, generate and translocate ammonium ( [Schjoerring et al., 2002](#B61) ). Therefore it could be ideal as a signaling molecule. In human cells ammonium has been shown to trigger autophagy ( [Eng et al., 2010](#B16) ), where the ammonium was derived from the deamination of glutamine by glutaminolysis. Astrocyte dysfunction mediated by ammonium involved interactions with antioxidants, oxidative stress and MAP kinases ( [Jayakumar et al., 2006](#B27) ). The same group reported that ammonium induced Ca 2+ increases in cells and suggested that this could lead to the synthesis of NO and ROS, and would involve proteins such as NAPDH oxidase, NOS, phospholipase A 2 and NF-κB ( [Norenberg et al., 2009](#B50) ). Therefore ammonium was acting on pathways in a similar way to other reactive compounds.

Methane has been shown to alter bowel contractile movement ( [Pimentel et al., 2006](#B57) ). The methane in this case was produced by bacteria in the gut flora. Another compound which may need to be considered is sulfur dioxide, which has been shown to reduce the proliferation of smooth muscle cells through a mechanism which involves MAP kinases and cAMP signaling (including activation of cAMP-dependent protein kinase: [Liu et al., 2014](#B38) ). Both these compounds therefore impinge on signaling in animals.

A molecule that has had a lot of recent interest in signaling is hydrogen gas. In animals for example, in a study on ischemia/reperfusion injury of liver, hydrogen gas was found to activate the NF-κB pathway ( [Zhang et al., 2015](#B71) ). This seems to be a convergence point of several of these signal transduction pathways, being implicated in ROS signaling ( [Morgan and Liu, 2011](#B47) ), NO signaling ( [Arias-Salvatierra et al., 2011](#B2) ) and H 2 S effects ( [Sen et al., 2012](#B62) ). In plants hydrogen gas has been found to be involved in a range of stress responses, just as seen with ROS, NO, and H 2 S. [Zhu et al. (2016)](#B74) in the introduction of their paper lists salt stress, toxicity of metals such as cadmium, aluminum and mercury, and oxidative stress. They go on to say that hydrogen gas inhibited NO production in animals ( [Itoh et al., 2011](#B26) ), and then showed that in plants hydrogen gas-induced generation of adventitious roots required NO in the downstream signaling cascades ( [Zhu et al., 2016](#B74) ). Therefore, as with the other reactive compounds discussed above, hydrogen gas impinges on these signaling systems and should be considered along with the other reactive molecules for a full understanding of signaling in plants.

Lastly, it is noteworthy that the understanding of how some of these reactive signals are working may have practical implications. It has been suggested that H 2 S and hydrogen gas may slow fruit ripening and senescence ( [Hu et al., 2012](#B25) , [2014](#B24) ), while in animal research H 2 S has been mooted as an important future therapeutic agent ( [Zhang et al., 2013](#B73) ). Low levels of such compounds have even been shown to increase life-span in some organisms ( [Miller and Roth, 2007](#B44) ), despite their inherent toxicity.

In conclusion, there has been much interest in how ROS, NO, and H 2 S are used as signals in cells, including in plants. They have been tolerated and harnessed during evolution but there are other reactive compounds which need to be embraced into this suite of signaling compounds, along with the interactions which take place between them, before it can be fully understood how this signaling works. Dysfunction of such signaling can have catastrophic results, while prudent use of some of these compounds may be of an advantage to future agriculture and therapeutics.

## Author Contributions

This is an invited inaugural paper as I was invited to be Associate Editor of Plant Physiology (specialty section of Frontiers in Physiology and Frontiers in Plant Science). I have written a mini-review with an opinion build in so have suggested that it should be a Perspective – hope this is correct. I am the sole author.

## Conflict of Interest Statement

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Acknowledgment

I would like to thank Dr. David Veal (UWE, Bristol) for his critical reading of this manuscript.

## References

Alvarez, C., Calo, L., Romero, L. C., Garcia, I., and Goor, C. (2010). An O-acetylserine(thiol)lyase homolog with L-cysteine desulfhydrase activity regulates cysteine homeostasis in *Arabidopsis* . *Plant Physiol.* 152, 656–669. doi: 10. 1104/pp. 109. 147975

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=19955263) | [CrossRef Full Text](https://doi.org/10.1104/pp.109.147975) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=An+O-acetylserine(thiol)lyase+homolog+with+L-cysteine+desulfhydrase+activity+regulates+cysteine+homeostasis+in+Arabidopsis.&journal=Plant+Physiol.&author=Alvarez+C.&author=Calo+L.&author=Romero+L.++C.&author=Garcia+I.&author=and+Goor+C.&publication_year=2010&volume=152&pages=656-669)

Arias-Salvatierra, D., Silbergeld, E. K., Acosta-Saavedra, L. C., and Calderon-Aranda, E. S. (2011). Role of nitric oxide produced by iNOS through NF-κB pathway in migration of cerebellar granule neurons induced by lipopolysaccharide. *Cell Signal.* 23, 425–435. doi: 10. 1016/j. cellsig. 2010. 10. 017

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=20955790) | [CrossRef Full Text](https://doi.org/10.1016/j.cellsig.2010.10.017) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Role+of+nitric+oxide+produced+by+iNOS+through+NF-κB+pathway+in+migration+of+cerebellar+granule+neurons+induced+by+lipopolysaccharide.&journal=Cell+Signal.&author=Arias-Salvatierra+D.&author=Silbergeld+E.++K.&author=Acosta-Saavedra+L.++C.&author=and+Calderon-Aranda+E.++S.&publication_year=2011&volume=23&pages=425-435)

Bartosz, G. (1996). Peroxynitrite: mediator of the toxic action of nitric oxide. *Acta Biochim. Pol.* 43, 645–659.

[Google Scholar](http://scholar.google.com/scholar_lookup?&title=Peroxynitrite%3A+mediator+of+the+toxic+action+of+nitric+oxide.&journal=Acta+Biochim.+Pol.&author=Bartosz+G.&publication_year=1996&volume=43&pages=645-659)

Blokhina, O., Virolainen, E., and Fagerstedt, K. V. (2003). Antioxidants, oxidative damage and oxygen deprivation stress: a review. *Ann. Bot.* 91, 179–194. doi: 10. 1093/aob/mcf118

[CrossRef Full Text](https://doi.org/10.1093/aob/mcf118) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Antioxidants%2C+oxidative+damage+and+oxygen+deprivation+stress%3A+a+review.&journal=Ann.++Bot.&author=Blokhina+O.&author=Virolainen+E.&author=and+Fagerstedt+K.+V.&publication_year=2003&volume=91&pages=179-194)

Bouillaud, F., Ransy, C., and Andriamihaja, M. (2013). Sulfide and mitochondrial bioenergetics. *Nitric Oxide* 31, S15. doi: 10. 1016/j. niox. 2013. 06. 021

[CrossRef Full Text](https://doi.org/10.1016/j.niox.2013.06.021 ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Sulfide+and+mitochondrial+bioenergetics.&journal=Nitric+Oxide&author=Bouillaud+F.&author=Ransy+C.&author=and+Andriamihaja+M.&publication_year=2013&volume=31)

Brandes, J. A., Boctor, N. Z., Cody, G. D., Cooper, B. A., Hazen, R. M., and Yoder, H. S. Jr. (1998). Abiotic nitrogen reduction on the early Earth. *Nature* 395, 365–367. doi: 10. 1038/26450

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=9759725) | [CrossRef Full Text](https://doi.org/10.1038/26450) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Abiotic+nitrogen+reduction+on+the+early+Earth.&journal=Nature&author=Brandes+J.+A.&author=Boctor+N.+Z.&author=Cody+G.+D.&author=Cooper+B.+A.&author=Hazen+R.+M.&author=and+Yoder+H.+S.+Jr.&publication_year=1998&volume=395&pages=365-367)

Britto, D. T., and Kronzucker, H. J. (2002). NH4 + toxicity in higher plants: a critical review. *J. Plant Physiol.* 159, 567–584. doi: 10. 1078/0176-1617-0774

[CrossRef Full Text](https://doi.org/10.1078/0176-1617-0774) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=NH4%2B+toxicity+in+higher+plants%3A+a+critical+review.&journal=J.+Plant+Physiol.&author=Britto+D.+T.&author=and+Kronzucker+H.+J.&publication_year=2002&volume=159&pages=567-584)

Calderwood, A., and Kopriva, S. (2014). Hydrogen sulfide in plants: from dissipation of excess sulfur to signaling molecule. *Nitric Oxide* 41, 72–78. doi: 10. 1016/j. niox. 2014. 02. 005

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24582856) | [CrossRef Full Text](https://doi.org/10.1016/j.niox.2014.02.005) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+in+plants%3A+from+dissipation+of+excess+sulfur+to+signaling+molecule.&journal=Nitric+Oxide&author=Calderwood+A.&author=and+Kopriva+S.&publication_year=2014&volume=41&pages=72-78)

Cheeseman, K. H., and Slater, T. F. (1993). An introduction to free radical biochemistry. *Br. Med. Bull.* 49, 481–493.

[Google Scholar](http://scholar.google.com/scholar_lookup?&title=An+introduction+to+free+radical+biochemistry.&journal=Br.+Med.+Bull.&author=Cheeseman+K.+H.&author=and+Slater+T.+F.&publication_year=1993&volume=49&pages=481-493)

Clarke, P. H. (1953). Hydrogen sulfide production by bacteria. *J. Gen. Microbiol.* 8, 397–407. doi: 10. 1099/00221287-8-3-397

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=13061742) | [CrossRef Full Text](https://doi.org/10.1099/00221287-8-3-397) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+production+by+bacteria.&journal=J.++Gen.++Microbiol.&author=Clarke+P.++H.&publication_year=1953&volume=8&pages=397-407)

Davidson, E. A. (1991). Sources of nitric oxide and nitrous oxide following wetting of dry oil. *Soil Sci. Soc. Am.* 56, 95–102. doi: 10. 2136/sssaj1992. 03615995005600010015x

[CrossRef Full Text](https://doi.org/10.2136/sssaj1992.03615995005600010015x)

De Kok, J. L., Bosma, W., Maas, F. M., and Kuiper, P. J. C. (1985). The effect of short-term H2S fumigation on water-soluble sulfydryl and glutathione levels in spinach. *Plant Cell Environ.* 8, 189–194. doi: 10. 1111/1365-3040. ep11604605

[CrossRef Full Text](https://doi.org/10.1111/1365-3040.ep11604605) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=The+effect+of+short-term+H2S+fumigation+on+water-soluble+sulfydryl+and+glutathione+levels+in+spinach.&journal=Plant+Cell+Environ.&author=De+Kok+J.+L.&author=Bosma+W.&author=Maas+F.+M.&author=and+Kuiper+P.+J.+C.&publication_year=1985&volume=8&pages=189-194)

Dooley, F. D., Nair, S. P., and Ward, P. D. (2013). Increased growth and germination success in plants following hydrogen sulfide administration. *PLoS ONE* 8: e62048. doi: 10. 1371/journal. pone. 0062048

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=23614010) | [CrossRef Full Text](https://doi.org/10.1371/journal.pone.0062048) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Increased+growth+and+germination+success+in+plants+following+hydrogen+sulfide+administration.&journal=PLoS+ONE&author=Dooley+F.+D.&author=Nair+S.+P.&author=and+Ward+P.+D.&publication_year=2013)

Dorman, D. C., Moulin, F. J., McManus, B. E., Mahle, K. C., James, R. A., and Struve, M. F. (2002). Cytochrome oxidase inhibition induced by acute hydrogen sulfide inhalation: correlation with tissue sulfide concentrations in the rat brain, liver, lung, and nasal epithelium. *Toxicol. Sci.* 65, 18–25. doi: 10. 1093/toxsci/65. 1. 18

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=11752681) | [CrossRef Full Text](https://doi.org/10.1093/toxsci/65.1.18) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Cytochrome+oxidase+inhibition+induced+by+acute+hydrogen+sulfide+inhalation%3A+correlation+with+tissue+sulfide+concentrations+in+the+rat+brain%2C+liver%2C+lung%2C+and+nasal+epithelium.&journal=Toxicol.+Sci.&author=Dorman+D.+C.&author=Moulin+F.+J.&author=McManus+B.+E.&author=Mahle+K.+C.&author=James+R.++A.&author=and+Struve+M.+F.&publication_year=2002&volume=65&pages=18-25)

Dowling, D. K., and Simmons, L. W. (2009). Reactive oxygen species as universal constraints in life-history evolution. *Proc. R. Soc. B* 276, 1737–1745. doi: 10. 1098/rspb. 2008. 1791

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=19324792) | [CrossRef Full Text](https://doi.org/10.1098/rspb.2008.1791 ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Reactive+oxygen+species+as+universal+constraints+in+life-history+evolution.&journal=Proc.+R.+Soc.+B&author=Dowling+D.+K.&author=and+Simmons+L.+W.&publication_year=2009&volume=276&pages=1737-1745)

Eng, C. H., Yu, K., Lucas, J., White, E., and Abraham, R. T. (2010). Ammonia derived from glutaminolysis is a diffusible regulator of autophagy. *Sci. Signal.* 3: ra31. doi: 10. 1126/scisignal. 2000911

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=20424262) | [CrossRef Full Text](https://doi.org/10.1126/scisignal.2000911) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Ammonia+derived+from+glutaminolysis+is+a+diffusible+regulator+of+autophagy.&journal=Sci.+Signal.&author=Eng+C.++H.&author=Yu+K.&author=Lucas+J.&author=White+E.&author=and+Abraham+R.++T.&publication_year=2010)

García-Mata, C., and Lamattina, L. (2013). Gasotransmitters are emerging as new guard cell signaling molecules and regulators of leaf gas exchange. *Plant Sci.* 201-202, 66–73. doi: 10. 1016/j. plantsci. 2012. 11. 007

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=23352403) | [CrossRef Full Text](https://doi.org/10.1016/j.plantsci.2012.11.007) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Gasotransmitters+are+emerging+as+new+guard+cell+signaling+molecules+and+regulators+of+leaf+gas+exchange.&journal=Plant+Sci.&author=García-Mata+C.&author=and+Lamattina+L.&publication_year=2013&volume=202&pages=66-73)

Gross, I., and Durner, J. (2016). In search of enzymes with a role in 3′, 5′-cyclic guanosine monophosphate metabolism in plants. *Front. Plant Sci.* 7: 576. doi: 10. 3389/fpls. 2016. 00576

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=27200049) | [CrossRef Full Text](https://doi.org/10.3389/fpls.2016.00576) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=In+search+of+enzymes+with+a+role+in+3′%2C+5′-cyclic+guanosine+monophosphate+metabolism+in+plants.&journal=Front.+Plant+Sci.&author=Gross+I.&author=and+Durner+J.&publication_year=2016)

Halliwell, B., and Gutteridge, J. (2015). *Free Radicals in Biology and Medicine* , 5th Edn. Oxford: Oxford University Press.

[Google Scholar](http://scholar.google.com/scholar_lookup?&title=Free+Radicals+in+Biology+and+Medicine&author=Halliwell+B.&author=and+Gutteridge+J.&publication_year=2015)

Hancock, J. T. (2016). *Cell Signalling* , 4th Edn. Oxford: Oxford University Press.

[Google Scholar](http://scholar.google.com/scholar_lookup?&title=Cell+Signalling&author=Hancock+J.+T.&publication_year=2016)

Hancock, J. T., Henson, D., Nyirenda, M., Desikan, R., Harrison, J., Lewis, M., et al. (2005). Proteomic identification of glyceraldehyde 3-phosphate dehydrogenase as an inhibitory target of hydrogen peroxide in *Arabidopsis* . *Plant Physiol. Biochem.* 43, 828–835. doi: 10. 1016/j. plaphy. 2005. 07. 012

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=16289945) | [CrossRef Full Text](https://doi.org/10.1016/j.plaphy.2005.07.012) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Proteomic+identification+of+glyceraldehyde+3-phosphate+dehydrogenase+as+an+inhibitory+target+of+hydrogen+peroxide+in+Arabidopsis.&journal=Plant+Physiol.+Biochem.&author=Hancock+J.+T.&author=Henson+D.&author=Nyirenda+M.&author=Desikan+R.&author=Harrison+J.&author=Lewis+M.&publication_year=2005&volume=43&pages=828-835)

Hancock, J. T., and Whiteman, M. (2014). Hydrogen sulfide and cell signaling: team player or referee? *Plant Physiol. Biochem.* 78, 37–42. doi: 10. 1016/j. plaphy. 2014. 02. 012

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24607577) | [CrossRef Full Text](https://doi.org/10.1016/j.plaphy.2014.02.012) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+and+cell+signaling%3A+team+player+or+referee%B4&journal=Plant+Physiol.++Biochem.&author=Hancock+J.++T.&author=and+Whiteman+M.&publication_year=2014&volume=78&pages=37-42)

Hancock, J. T., and Whiteman, M. (2015). Hydrogen sulfide signaling: interactions with nitric oxide and reactive oxygen species. *Ann. N. Y. Acad. Sci* 1365, 5–14. doi: 10. 1111/nyas. 12733

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=25782612) | [CrossRef Full Text](https://doi.org/10.1111/nyas.12733) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+signaling%3A+interactions+with+nitric+oxide+and+reactive+oxygen+species.&journal=Ann.+N.+Y.+Acad.++Sci&author=Hancock+J.++T.&author=and+Whiteman+M.&publication_year=2015&volume=1365&pages=5-14)

Hu, H., Li, P., Wang, Y., and Gu, R. (2014). Hydrogen-rich water delays postharvest ripening and senescence of kiwifruit. *Food Chem.* 156, 100–109. doi: 10. 1016/j. foodchem. 2014. 01. 067

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24629944) | [CrossRef Full Text](https://doi.org/10.1016/j.foodchem.2014.01.067) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen-rich+water+delays+postharvest+ripening+and+senescence+of+kiwifruit.&journal=Food+Chem.&author=Hu+H.&author=Li+P.&author=Wang+Y.&author=and+Gu+R.&publication_year=2014&volume=156&pages=100-109)

Hu, L.-Y., Hu, S.-L., Wu, J., Li, Y.-H., Zheng, J.-L., Wei, Z.-J., et al. (2012). Hydrogen sulfide prolongs postharvest shelf life of strawberry and plays an antioxidative role in fruits. *J. Agric. Food Chem.* 60, 8684–8693. doi: 10. 1021/jf300728h

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=22871304) | [CrossRef Full Text](https://doi.org/10.1021/jf300728h ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+prolongs+postharvest+shelf+life+of+strawberry+and+plays+an+antioxidative+role+in+fruits.&journal=J.+Agric.+Food+Chem.&author=Hu+L.-Y.&author=Hu+S.-L.&author=Wu+J.&author=Li+Y.-H.&author=Zheng+J.-L.&author=Wei+Z.-J.&publication_year=2012&volume=60&pages=8684-8693)

Itoh, T., Hamada, N., Terazawa, R., Ito, M., Ohno, K., Ichihara, M., et al. (2011). Molecular hydrogen inhibits lipopolysaccharide/interferon γ-induced nitric oxide production through modulation of signal transduction in macrophages. *Biochem. Biophys. Res. Commun.* 411, 143–149. doi: 10. 1016/j. bbrc. 2011. 06. 116

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=21723254) | [CrossRef Full Text](https://doi.org/10.1016/j.bbrc.2011.06.116) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Molecular+hydrogen+inhibits+lipopolysaccharide%2Finterferon+γ-induced+nitric+oxide+production+through+modulation+of+signal+transduction+in+macrophages.&journal=Biochem.++Biophys.++Res.++Commun.&author=Itoh+T.&author=Hamada+N.&author=Terazawa+R.&author=Ito+M.&author=Ohno+K.&author=Ichihara+M.&publication_year=2011&volume=411&pages=143-149)

Jayakumar, A. R., Panickar, K. S., Murthy, Ch. R., and Norenberg, M. D. (2006). Oxidative stress and mitogen-activated protein kinase phosphorylation mediate ammonia-induced cell swelling and glutamate uptake inhibition in cultured astrocytes. *J. Neurosci.* 26, 4774–4784. doi: 10. 1523/JNEUROSCI. 0120-06. 2006

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=16672650) | [CrossRef Full Text](https://doi.org/10.1523/JNEUROSCI.0120-06.2006) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Oxidative+stress+and+mitogen-activated+protein+kinase+phosphorylation+mediate+ammonia-induced+cell+swelling+and+glutamate+uptake+inhibition+in+cultured+astrocytes.&journal=J.++Neurosci.&author=Jayakumar+A.++R.&author=Panickar+K.++S.&author=Murthy+Ch.++R.&author=and+Norenberg+M.++D.&publication_year=2006&volume=26&pages=4774-4784)

Jeandroz, S., Wipf, D., Stuerhr, D. J., Lamattina, L., Melkonian, M., Tian, Z., et al. (2016). Occurrence, structure, and evolution of nitric oxide synthase-like proteins in the plant kingdom. *Sci. Signal.* 9, re2. doi: 10. 1126/scisignal. aad4403

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=26933064) | [CrossRef Full Text](https://doi.org/10.1126/scisignal.aad4403) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Occurrence%2C+structure%2C+and+evolution+of+nitric+oxide+synthase-like+proteins+in+the+plant+kingdom.&journal=Sci.+Signal.&author=Jeandroz+S.&author=Wipf+D.&author=Stuerhr+D.++J.&author=Lamattina+L.&author=Melkonian+M.&author=Tian+Z.&publication_year=2016&volume=9)

Jena, N. R. (2012). DNA damage by reactive species: mechanisms, mutation and repair. *J. Biosci.* 37, 503–517. doi: 10. 1007/s12038-012-9218-2

[CrossRef Full Text](https://doi.org/10.1007/s12038-012-9218-2) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=DNA+damage+by+reactive+species%3A+mechanisms%2C+mutation+and+repair.&journal=J.+Biosci.&author=Jena+N.+R.&publication_year=2012&volume=37&pages=503-517)

Kelley, J. L., Arias-Rodriguez, L., Martin, D. P., Yee, M.-C., Bustamante, C. D., and Tobler, M. (2016). Mechanisms underlying adaptation to life in hydrogen sulfide rich environments. *Mol. Biol. Evol.* 33, 1419–1434. doi: 10. 1093/molbev/msw020

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=26861137) | [CrossRef Full Text](https://doi.org/10.1093/molbev/msw020) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Mechanisms+underlying+adaptation+to+life+in+hydrogen+sulfide+rich+environments.&journal=Mol.+Biol.+Evol.&author=Kelley+J.+L.&author=Arias-Rodriguez+L.&author=Martin+D.+P.&author=Yee+M.-C.&author=Bustamante+C.++D.&author=and+Tobler+M.&publication_year=2016&volume=33&pages=1419-1434)

Klotz, L.-O. (2005). Oxidant-induced signaling: effects of peroxynitrite and singlet oxygen. *Biol. Chem.* 383, 443–456. doi: 10. 1515/BC. 2002. 047

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=12033434) | [CrossRef Full Text](https://doi.org/10.1515/BC.2002.047) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Oxidant-induced+signaling%3A+effects+of+peroxynitrite+and+singlet+oxygen.&journal=Biol.+Chem.&author=Klotz+L.-O.&publication_year=2005&volume=383&pages=443-456)

Kovtun, Y., Chiu, W. L., Tena, G., and Sheen, J. (2000). Functional analysis of oxidative stress-activated mitogen-activated protein kinase cascade in plants. *Proc. Natl. Acad. Sci. U. S. A.* 97, 2940–2945. doi: 10. 1073/pnas. 97. 6. 2940

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=10717008) | [CrossRef Full Text](https://doi.org/10.1073/pnas.97.6.2940) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Functional+analysis+of+oxidative+stress-activated+mitogen-activated+protein+kinase+cascade+in+plants.&journal=Proc.+Natl.+Acad.+Sci.+U.S.A.&author=Kovtun+Y.&author=Chiu+W.+L.&author=Tena+G.&author=and+Sheen+J.&publication_year=2000&volume=97&pages=2940-2945)

Lane, N. (2002). *Oxygen: The Molecule that Made the World* . Oxford: Oxford University Press.

[Google Scholar](http://scholar.google.com/scholar_lookup?&title=Oxygen%3A+The+Molecule+that+Made+the+World.&author=Lane+N.&publication_year=2002)

Li, J., Jia, H., Wang, J., Cao, Q., and Wen, Z. (2013). Hydrogen sulfide is involved in maintaining ion homeostasis via regulating plasma membrane Na + /H + antiporter system in the hydrogen peroxide-dependent manner in salt-stress *Arabidopsis thaliana* root. *Protoplasma* 251, 899–912. doi: 10. 1007/s00709-013-0592-x

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24318675) | [CrossRef Full Text](https://doi.org/10.1007/s00709-013-0592-x ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+is+involved+in+maintaining+ion+homeostasis+via+regulating+plasma+membrane+Na%2B%2FH%2B+antiporter+system+in+the+hydrogen+peroxide-dependent+manner+in+salt-stress+Arabidopsis+thaliana+root.&journal=Protoplasma&author=Li+J.&author=Jia+H.&author=Wang+J.&author=Cao+Q.&author=and+Wen+Z.&publication_year=2013&volume=251&pages=899-912)

Li, Q., and Lancaster, J. R. Jr. (2013). Chemical foundations of hydrogen sulfide biology. *Nitric Oxide* 35, 21–34. doi: 10. 1016/j. niox. 2013. 07. 001

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=23850631) | [CrossRef Full Text](https://doi.org/10.1016/j.niox.2013.07.001) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Chemical+foundations+of+hydrogen+sulfide+biology.&journal=Nitric+Oxide&author=Li+Q.&author=and+Lancaster+J.+R.+Jr.&publication_year=2013&volume=35&pages=21-34)

Lindermayr, C., Sallbach, G., and Durner, J. (2005). Proteomic identification of S-nitrosylated proteins in *Arabidopsis* . *Plant Physiol.* 137, 921–930. doi: 10. 1104/pp. 104. 058719

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=15734904) | [CrossRef Full Text](https://doi.org/10.1104/pp.104.058719) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Proteomic+identification+of+S-nitrosylated+proteins+in+Arabidopsis.&journal=Plant+Physiol.&author=Lindermayr+C.&author=Sallbach+G.&author=and+Durner+J.&publication_year=2005&volume=137&pages=921-930)

Lisjak, M., Srivastava, N., Teklic, T., Civale, L., Lewandowski, K., Wilson, I., et al. (2010). A novel hydrogen sulfide donor causes stomatal opening and reduces nitric oxide accumulation. *Plant Physiol. Biochem.* 48, 931–935. doi: 10. 1016/j. plaphy. 2010. 09. 016

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=20970349) | [CrossRef Full Text](https://doi.org/10.1016/j.plaphy.2010.09.016) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=A+novel+hydrogen+sulfide+donor+causes+stomatal+opening+and+reduces+nitric+oxide+accumulation.&journal=Plant+Physiol.+Biochem.&author=Lisjak+M.&author=Srivastava+N.&author=Teklic+T.&author=Civale+L.&author=Lewandowski+K.&author=Wilson+I.&publication_year=2010&volume=48&pages=931-935)

Liu, D., Huang, Y., Bu, D., Liu, A. D., Holmberg, L., Jian, Y., et al. (2014). Sulfur dioxide inhibits vascular smooth muscle cell proliferation via suppressing the Erk/MAP kinase pathway mediated by cAMP/PKA signaling. *Cell Death Dis.* 5, e1251. doi: 10. 1038/cddis. 2014. 229

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24853429) | [CrossRef Full Text](https://doi.org/10.1038/cddis.2014.229) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Sulfur+dioxide+inhibits+vascular+smooth+muscle+cell+proliferation+via+suppressing+the+Erk%2FMAP+kinase+pathway+mediated+by+cAMP%2FPKA+signaling.&journal=Cell+Death+Dis.&author=Liu+D.&author=Huang+Y.&author=Bu+D.&author=Liu+A.+D.&author=Holmberg+L.&author=Jian+Y.&publication_year=2014&volume=5)

Ludwig, J., Meixner, F. X., Vogel, B., and Förstner, J. (2001). Soil-air exchange of nitric oxide: an overview of processes, environmental factors, and modeling studies. *Biogeochemistry* 52, 225–257. doi: 10. 1023/A: 1006424330555

[CrossRef Full Text](https://doi.org/10.1023/A: 1006424330555) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Soil-air+exchange+of+nitric+oxide%3A+an+overview+of+processes%2C+environmental+factors%2C+and+modeling+studies.&journal=Biogeochemistry&author=Ludwig+J.&author=Meixner+F.+X.&author=Vogel+B.&author=and+Förstner+J.&publication_year=2001&volume=52&pages=225-257)

Lyons, T. W., Reinhard, C. T., and Planavsky, N. J. (2014). The rise of oxygen in Earth’s early ocean and atmosphere. *Nature* 506, 307–315. doi: 10. 1038/nature13068

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24553238) | [CrossRef Full Text](https://doi.org/10.1038/nature13068) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=The+rise+of+oxygen+in+Earth's+early+ocean+and+atmosphere.&journal=Nature&author=Lyons+T.+W.&author=Reinhard+C.+T.&author=and+Planavsky+N.+J.&publication_year=2014&volume=506&pages=307-315)

Martin, W., Baross, J., Kelley, D., and Russell, M. J. (2008). Hydrothermal vents and the origin of life. *Nat. Rev. Microbiol.* 6, 805–814. doi: 10. 1038/nrmicro1991

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=18820700) | [CrossRef Full Text](https://doi.org/10.1038/nrmicro1991) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrothermal+vents+and+the+origin+of+life.&journal=Nat.++Rev.++Microbiol.&author=Martin+W.&author=Baross+J.&author=Kelley+D.&author=and+Russell+M.+J.&publication_year=2008&volume=6&pages=805-814)

Mata-Pérez, C., Sánchez-Calvo, B., Padila, M. N., Begara-Morales, J. C., Lugue, F., Melguizo, M., et al. (2016). Nitro-fatty acids in plant signalling: nitro-linolenic acid induces the molecular chaperone network in *Arabidopsis* . *Plant Physiol.* 170, 686–701. doi: 10. 1104/pp. 15. 01671

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=26628746) | [CrossRef Full Text](https://doi.org/10.1104/pp.15.01671) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Nitro-fatty+acids+in+plant+signalling%3A+nitro-linolenic+acid+induces+the+molecular+chaperone+network+in+Arabidopsis.&journal=Plant+Physiol.&author=Mata-Pérez+C.&author=Sánchez-Calvo+B.&author=Padila+M.+N.&author=Begara-Morales+J.+C.&author=Lugue+F.&author=Melguizo+M.&publication_year=2016&volume=170&pages=686-701)

Metcalfe, N. B., and Alonso-Alvarez, C. (2010). Oxidative stress as a life-history constraint: the role of reactive oxygen species in shaping phenotypes from conception to death. *Funct. Ecol.* 24, 984–996. doi: 10. 1111/j. 1365-2435. 2010. 01750. x

[CrossRef Full Text](https://doi.org/10.1111/j.1365-2435.2010.01750.x ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Oxidative+stress+as+a+life-history+constraint%3A+the+role+of+reactive+oxygen+species+in+shaping+phenotypes+from+conception+to+death.&journal=Funct.++Ecol.&author=Metcalfe+N.++B.&author=and+Alonso-Alvarez+C.&publication_year=2010&volume=24&pages=984-996)

Miller, D. L., and Roth, M. B. (2007). Hydrogen sulfide increases thermotolerance and lifespan in *Caenorhabditis elegans* . *Proc. Natl. Acad. Sci. U. S. A.* 104, 20618–20622. doi: 10. 1073/pnas. 0710191104

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=18077331) | [CrossRef Full Text](https://doi.org/10.1073/pnas.0710191104) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+increases+thermotolerance+and+lifespan+in+Caenorhabditis+elegans.&journal=Proc.+Natl.+Acad.+Sci.++U.S.A.&author=Miller+D.++L.&author=and+Roth+M.++B.&publication_year=2007&volume=104&pages=20618-20622)

Misra, A. N., Misra, M., and Singh, R. (2011). Nitric oxide ameliorates stress responses in plants. *Plant Soil Environ.* 57, 95–100.

[Google Scholar](http://scholar.google.com/scholar_lookup?&title=Nitric+oxide+ameliorates+stress+responses+in+plants.&journal=Plant+Soil+Environ.&author=Misra+A.+N.&author=Misra+M.&author=and+Singh+R.&publication_year=2011&volume=57&pages=95-100)

Mittler, R., Vanderauwera, S., Suzuki, N., Miller, G., Tognetti, V. B., Vandepoele, K., et al. (2011). ROS signalling: the new wave? *Trends Plant Sci.* 16, 300–309. doi: 10. 1016/j. tplants. 2011. 03. 007

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=21482172) | [CrossRef Full Text](https://doi.org/10.1016/j.tplants.2011.03.007) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=ROS+signalling%3A+the+new+wave%B4&journal=Trends+Plant+Sci.&author=Mittler+R.&author=Vanderauwera+S.&author=Suzuki+N.&author=Miller+G.&author=Tognetti+V.++B.&author=Vandepoele+K.&publication_year=2011&volume=16&pages=300-309)

Morgan, M. J., and Liu, Z.-G. (2011). Crosstalk of reactive oxygen species and NF-κB signaling. *Cell Res.* 21, 103–115. doi: 10. 1038/cr. 2010. 178

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=21187859) | [CrossRef Full Text](https://doi.org/10.1038/cr.2010.178) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Crosstalk+of+reactive+oxygen+species+and+NF-κB+signaling.&journal=Cell+Res.&author=Morgan+M.+J.&author=and+Liu+Z.-G.&publication_year=2011&volume=21&pages=103-115)

Mur, L. A. J., Mandon, J., Persijn, S., Cristescu, S. M., Moshkov, I. E., Novikova, G. V., et al. (2013). Nitric oxide in plants: an assessment of the current state of knowledge. *AoB Plants* 5: pls052. doi: 10. 1093/aobpla/pls052

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=23372921) | [CrossRef Full Text](https://doi.org/10.1093/aobpla/pls052) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Nitric+oxide+in+plants%3A+an+assessment+of+the+current+state+of+knowledge.&journal=AoB+Plants&author=Mur+L.+A.+J.&author=Mandon+J.&author=Persijn+S.&author=Cristescu+S.+M.&author=Moshkov+I.+E.&author=Novikova+G.+V.&publication_year=2013)

Murata, Y., Mori, I. C., and Munemasa, S. (2015). Diverse stomatal signaling and the signal integration mechanism. *Annu. Rev. Plant Biol.* 66, 369–392. doi: 10. 1146/annurev-arplant-043014-114707

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=25665132) | [CrossRef Full Text](https://doi.org/10.1146/annurev-arplant-043014-114707) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Diverse+stomatal+signaling+and+the+signal+integration+mechanism.&journal=Annu.+Rev.+Plant+Biol.&author=Murata+Y.&author=Mori+I.+C.&author=and+Munemasa+S.&publication_year=2015&volume=66&pages=369-392)

Norenberg, M. D., Rama Rao, K. V., and Jayakumar, A. R. (2009). Signaling factors in the mechanism of ammonia neurotoxicity. *Metab. Brain Dis.* 24, 103–117. doi: 10. 1007/s11011-008-9113-6

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=19104923) | [CrossRef Full Text](https://doi.org/10.1007/s11011-008-9113-6) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Signaling+factors+in+the+mechanism+of+ammonia+neurotoxicity.&journal=Metab.+Brain+Dis.&author=Norenberg+M.+D.&author=Rama+Rao+K.+V.&author=and+Jayakumar+A.+R.&publication_year=2009&volume=24&pages=103-117)

Olson, K. R., and Strub, K. D. (2015). The role of hydrogen sulfide in evolution and the evolution of hydrogen sulfide in metabolism and signaling. *Physiology* 31, 60–72. doi: 10. 1152/physiol. 00024. 2015

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=26674552) | [CrossRef Full Text](https://doi.org/10.1152/physiol.00024.2015) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=The+role+of+hydrogen+sulfide+in+evolution+and+the+evolution+of+hydrogen+sulfide+in+metabolism+and+signaling.&journal=Physiology&author=Olson+K.++R.&author=and+Strub+K.++D.&publication_year=2015&volume=31&pages=60-72)

Osuna, D., Prieto, P., and Aguilar, M. (2015). Control of seed germination and plant development by carbon and nitrogen availability. *Front. Plant Sci.* 6: 1023. doi: 10. 3389/fpls. 2015. 01023

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=26635847) | [CrossRef Full Text](https://doi.org/10.3389/fpls.2015.01023) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Control+of+seed+germination+and+plant+development+by+carbon+and+nitrogen+availability.&journal=Front.+Plant+Sci.&author=Osuna+D.&author=Prieto+P.&author=and+Aguilar+M.&publication_year=2015)

Palmer, R. M., Ferrige, A. G., and Moncada, S. (1987). Nitric oxide release accounts for the biological activity of endothelium-derived relaxing factor. *Nature* 327, 524–526. doi: 10. 1038/327524a0

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=3495737) | [CrossRef Full Text](https://doi.org/10.1038/327524a0 ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Nitric+oxide+release+accounts+for+the+biological+activity+of+endothelium-derived+relaxing+factor.&journal=Nature&author=Palmer+R.+M.&author=Ferrige+A.+G.&author=and+Moncada+S.&publication_year=1987&volume=327&pages=524-526)

Paquay, J. B. G., Haenen, G. R. M. M., Stender, G., Wiseman, S. A., Tijburg, L. B. M., and Bast, A. (2000). Protection against nitric oxide toxicity by tea. *J. Agric. Food Chem.* 48, 5768–5772. doi: 10. 1021/jf981316h

[CrossRef Full Text](https://doi.org/10.1021/jf981316h) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Protection+against+nitric+oxide+toxicity+by+tea.&journal=J.+Agric.+Food+Chem.&author=Paquay+J.+B.+G.&author=Haenen+G.+R.+M.+M.&author=Stender+G.&author=Wiseman+S.+A.&author=Tijburg+L.+B.+M.&author=and+Bast+A.&publication_year=2000&volume=48&pages=5768-5772)

Parkes, T. L., Elia, A. J., Dickinson, D., Hillikar, A. J., Phillips, J. P., and Boullianne, G. L. (1998). Extension of Drosophila lifespan by overexpression of human SOD1 in motorneurons. *Nat. Genet.* 19, 171–174. doi: 10. 1038/534

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=9620775) | [CrossRef Full Text](https://doi.org/10.1038/534) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Extension+of+Drosophila+lifespan+by+overexpression+of+human+SOD1+in+motorneurons.&journal=Nat.+Genet.&author=Parkes+T.+L.&author=Elia+A.+J.&author=Dickinson+D.&author=Hillikar+A.+J.&author=Phillips+J.+P.&author=and+Boullianne+G.+L.&publication_year=1998&volume=19&pages=171-174)

Petrov, V. D., and Van Breusegem, F. (2012). Hydrogen peroxide–a central hub for information flow in plant cells. *AoB Plants* 2012, ls014. doi: 10. 1093/aobpla/pls014

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=22708052) | [CrossRef Full Text](https://doi.org/10.1093/aobpla/pls014) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+peroxide-a+central+hub+for+information+flow+in+plant+cells.&journal=AoB+Plants&author=Petrov+V.++D.&author=and+Van+Breusegem+F.&publication_year=2012&volume=2012)

Pimentel, M., Lin, H. C., Enayati, P., van den Burg, B., Lee, H.-R., Chen, J. H., et al. (2006). Methane, a gas produced by enteric bacteria, slows intestinal transit and augments small intestinal contractile activity. *Am. J. Physiol. Gastrointest. Liver Physiol.* 290, G1089–G1095. doi: 10. 1152/ajpgi. 00574. 2004

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=16293652) | [CrossRef Full Text](https://doi.org/10.1152/ajpgi.00574.2004) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Methane%2C+a+gas+produced+by+enteric+bacteria%2C+slows+intestinal+transit+and+augments+small+intestinal+contractile+activity.&journal=Am.++J.++Physiol.++Gastrointest.+Liver+Physiol.&author=Pimentel+M.&author=Lin+H.+C.&author=Enayati+P.&author=van+den+Burg+B.&author=Lee+H.-R.&author=Chen+J.++H.&publication_year=2006&volume=290&pages=G1089-G1095)

Rockel, P., Strube, F., Rockel, A., Wildt, J., and Kaiser, W. M. (2002). Regulation of nitric oxide (NO) production by plant nitrate reductase in vivo and in vitro. *J. Exp. Bot.* 53, 103–110. doi: 10. 1093/jexbot/53. 366. 103

[CrossRef Full Text](https://doi.org/10.1093/jexbot/53.366.103) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Regulation+of+nitric+oxide+(NO)+production+by+plant+nitrate+reductase+in+vivo+and+in+vitro.&journal=J.+Exp.+Bot.&author=Rockel+P.&author=Strube+F.&author=Rockel+A.&author=Wildt+J.&author=and+Kaiser+W.+M.&publication_year=2002&volume=53&pages=103-110)

Romero, L. C., Aroca, M. A., Serna, A., and Gotor, C. (2013). Proteomic analysis of endogenous S-sulfhydration in *Arabidopsis thaliana* . *Nitric Oxide* 31, S23. doi: 10. 1016/j. niox. 2013. 06. 040

[CrossRef Full Text](https://doi.org/10.1016/j.niox.2013.06.040) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Proteomic+analysis+of+endogenous+S-sulfhydration+in+Arabidopsis+thaliana.&journal=Nitric+Oxide&author=Romero+L.+C.&author=Aroca+M.+A.&author=Serna+A.&author=and+Gotor+C.&publication_year=2013&volume=31)

Schafer, F. Q., and Buettner, G. R. (2001). Redox environment of the cell as viewed through the redox state of the glutathione disulfide/glutathione couple. *Free Radic. Biol. Med.* 30, 1191–1212. doi: 10. 1016/S0891-5849(01)00480-4 PMID: 11368918

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=11368918) | [CrossRef Full Text](https://doi.org/10.1016/S0891-5849(01)00480-4 PMID: 11368918) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Redox+environment+of+the+cell+as+viewed+through+the+redox+state+of+the+glutathione+disulfide%2Fglutathione+couple.&journal=Free+Radic.++Biol.++Med.&author=Schafer+F.+Q.&author=and+Buettner+G.+R.&publication_year=2001&volume=30&pages=1191-1212)

Schjoerring, J. K., Husted, S., Mäck, G., and Mattsson, M. (2002). The regulation of ammonium translocation in plants. *J. Exp. Bot.* 53, 883–890. doi: 10. 1093/jexbot/53. 370. 883

[CrossRef Full Text](https://doi.org/10.1093/jexbot/53.370.883) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=The+regulation+of+ammonium+translocation+in+plants.&journal=J.+Exp.+Bot.&author=Schjoerring+J.+K.&author=Husted+S.&author=Mäck+G.&author=and+Mattsson+M.&publication_year=2002&volume=53&pages=883-890)

Sen, N., Paul, B. D., Gadalla, M. M., Mustafa, A. K., Sen, T., Xu, R., et al. (2012). Hydrogen sulfide-linked sulfhydration of NF-κB mediates its antiapoptotic actions. *Mol. Cell.* 45, 13–24. doi: 10. 1016/j. molcel. 2011. 10. 021

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=22244329) | [CrossRef Full Text](https://doi.org/10.1016/j.molcel.2011.10.021 ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide-linked+sulfhydration+of+NF-κB+mediates+its+antiapoptotic+actions.&journal=Mol.+Cell.&author=Sen+N.&author=Paul+B.+D.&author=Gadalla+M.+M.&author=Mustafa+A.+K.&author=Sen+T.&author=Xu+R.&publication_year=2012&volume=45&pages=13-24)

Shan, C. J., Zhang, S. L., Li, D. F., Zhao, Y. Z., Tian, X. L., Zhao, X. L., et al. (2011). Effects of exogenous hydrogen sulfide on the ascorbate and glutathione metabolism in wheat seedlings leaves under water stress. *Acta Physiol. Plant.* 33, 2533–2540. doi: 10. 1007/s11738-011-0746-4

[CrossRef Full Text](https://doi.org/10.1007/s11738-011-0746-4) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Effects+of+exogenous+hydrogen+sulfide+on+the+ascorbate+and+glutathione+metabolism+in+wheat+seedlings+leaves+under+water+stress.&journal=Acta+Physiol.+Plant.&author=Shan+C.+J.&author=Zhang+S.+L.&author=Li+D.+F.&author=Zhao+Y.+Z.&author=Tian+X.+L.&author=Zhao+X.+L.&publication_year=2011&volume=33&pages=2533-2540)

Skiba, U., Smith, K. A., and Fowler, D. (1993). Nitrification and denitrification as sources of nitric oxide and nitrous oxide in sandy loam soil. *Soil Biol. Biochem.* 25, 1527–1536. doi: 10. 1073/pnas. 1219993110

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=23576736) | [CrossRef Full Text](https://doi.org/10.1073/pnas.1219993110) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Nitrification+and+denitrification+as+sources+of+nitric+oxide+and+nitrous+oxide+in+sandy+loam+soil.&journal=Soil+Biol.+Biochem.&author=Skiba+U.&author=Smith+K.++A.&author=and+Fowler+D.&publication_year=1993&volume=25&pages=1527-1536)

Szinicz, L. (2005). History of chemical and biological warfare agents. *Toxicology* 214, 167–181. doi: 10. 1016/j. tox. 2005. 06. 011

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=16111798) | [CrossRef Full Text](https://doi.org/10.1016/j.tox.2005.06.011) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=History+of+chemical+and+biological+warfare+agents.&journal=Toxicology&author=Szinicz+L.&publication_year=2005&volume=214&pages=167-181)

Tobler, M., Passow, C. N., Greenway, R., Kelley, J. L., and Shaw, J. H. (2016). The evolutionary ecology of animals inhabiting hydrogen sulfide–rich environments. *Annu. Rev. Ecol. Evol. Syst.* 47, 239–262. doi: 10. 1146/annurev-ecolsys-121415-032418

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=24033173) | [CrossRef Full Text](https://doi.org/10.1146/annurev-ecolsys-121415-032418) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=The+evolutionary+ecology+of+animals+inhabiting+hydrogen+sulfide-rich+environments.&journal=Annu.++Rev.++Ecol.++Evol.++Syst.&author=Tobler+M.&author=Passow+C.++N.&author=Greenway+R.&author=Kelley+J.++L.&author=and+Shaw+J.++H.&publication_year=2016&volume=47&pages=239-262)

Wallace, D. C., and Melov, S. (1998). Radicals r’aging. *Nat. Genet.* 19, 105–106. doi: 10. 1038/448

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=9620757) | [CrossRef Full Text](https://doi.org/10.1038/448) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Radicals+r'aging.&journal=Nat.+Genet.&author=Wallace+D.++C.&author=and+Melov+S.&publication_year=1998&volume=19&pages=105-106)

Wang, P., Du, Y., Li, Y., Ren, D., and Song, C. P. (2010). Hydrogen peroxide-mediated activation of MAP kinase 6 modulates nitric oxide biosynthesis and signal transduction in *Arabidopsis* . *Plant Cell* 22, 2981–2998. doi: 10. 1105/tpc. 109. 072959

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=20870959) | [CrossRef Full Text](https://doi.org/10.1105/tpc.109.072959) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+peroxide-mediated+activation+of+MAP+kinase+6+modulates+nitric+oxide+biosynthesis+and+signal+transduction+in+Arabidopsis.&journal=Plant+Cell&author=Wang+P.&author=Du+Y.&author=Li+Y.&author=Ren+D.&author=and+Song+C.++P.&publication_year=2010&volume=22&pages=2981-2998)

Whiteman, M., Li, L., Kostetski, I., Chu, S. H., Siau, J. L., Bhatia, M., et al. (2006). Evidence for the formation of a novel nitrosothiol from the gaseous mediators nitric oxide and hydrogen sulfide. *Biochem. Biophys. Res. Commun.* 343, 303–310. doi: 10. 1016/j. bbrc. 2006. 02. 154

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=16540095) | [CrossRef Full Text](https://doi.org/10.1016/j.bbrc.2006.02.154) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Evidence+for+the+formation+of+a+novel+nitrosothiol+from+the+gaseous+mediators+nitric+oxide+and+hydrogen+sulfide.&journal=Biochem.+Biophys.+Res.+Commun.&author=Whiteman+M.&author=Li+L.&author=Kostetski+I.&author=Chu+S.+H.&author=Siau+J.+L.&author=Bhatia+M.&publication_year=2006&volume=343&pages=303-310)

Youssefian, S., Nakamur, M., and Sano, H. (1993). Tobacco plants transformed with the O-acetylserine (thiol) lyase gene of wheat are resistant to toxic levels of hydrogen sulfide gas. *Plant J.* 4, 759–769. doi: 10. 1046/j. 1365-313X. 1993. 04050759. x

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=8275097) | [CrossRef Full Text](https://doi.org/10.1046/j.1365-313X.1993.04050759.x) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Tobacco+plants+transformed+with+the+O-acetylserine+(thiol)+lyase+gene+of+wheat+are+resistant+to+toxic+levels+of+hydrogen+sulfide+gas.&journal=Plant+J.&author=Youssefian+S.&author=Nakamur+M.&author=and+Sano+H.&publication_year=1993&volume=4&pages=759-769)

Zhang, C.-B., Tang, Y.-C., Xu, X.-J., Guo, S.-X., and Wang, H.-Z. (2015). Hydrogen gas inhalation protects against liver ischamia/reperfusion injury by activating the NF-kB signalling pathway. *Exp. Ther. Med.* 9, 2114–2120. doi: 10. 3892/etm. 2015. 2385

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=26136944) | [CrossRef Full Text](https://doi.org/10.3892/etm.2015.2385 ) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+gas+inhalation+protects+against+liver+ischamia%2Freperfusion+injury+by+activating+the+NF-kB+signalling+pathway.&journal=Exp.+Ther.+Med.&author=Zhang+C.-B.&author=Tang+Y.-C.&author=Xu+X.-J.&author=Guo+S.-X.&author=and+Wang+H.-Z.&publication_year=2015&volume=9&pages=2114-2120)

Zhang, H., Hu, S. L., Zhang, Z. J., Hu, L.-Y., Jiang, C.-X., Wei, Z.-J., et al. (2011). Hydrogen sulfide acts as a regulator of flower senescence in plants. *Postharv. Biol. Technol.* 60, 251–257. doi: 10. 1016/j. postharvbio. 2011. 01. 006

[CrossRef Full Text](https://doi.org/10.1016/j.postharvbio.2011.01.006) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide+acts+as+a+regulator+of+flower+senescence+in+plants.&journal=Postharv.+Biol.+Technol.&author=Zhang+H.&author=Hu+S.+L.&author=Zhang+Z.+J.&author=Hu+L.-Y.&author=Jiang+C.-X.&author=Wei+Z.-J.&publication_year=2011&volume=60&pages=251-257)

Zhang, Y., Tang, Z.-H., Ren, Z., Qu, S.-L., Liu, M.-H., Jiang, Z.-S., et al. (2013). Hydrogen sulfide, the next potent preventive and therapeutic agent in aging and age-related diseases. *Mol. Cell. Biol.* 33, 1104–1113. doi: 10. 1128/MCB. 01215-12

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=23297346) | [CrossRef Full Text](https://doi.org/10.1128/MCB.01215-12) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Hydrogen+sulfide%2C+the+next+potent+preventive+and+therapeutic+agent+in+aging+and+age-related+diseases.&journal=Mol.+Cell.+Biol.&author=Zhang+Y.&author=Tang+Z.-H.&author=Ren+Z.&author=Qu+S.-L.&author=Liu+M.-H.&author=Jiang+Z.-S.&publication_year=2013&volume=33&pages=1104-1113)

Zhu, Y., Liao, W., Wang, M., Niu, L., Xu, Q., and Jin, X. (2016). Nitric oxide is required for hydrogen gas-induced adventitious root formation in cucumber. *J. Plant Physiol.* 195, 50–58. doi: 10. 1016/j. jplph. 2016. 02. 018

[PubMed Abstract](http://www.ncbi.nlm.nih.gov/sites/entrez?Db=pubmed&Cmd=ShowDetailView&TermToSearch=27010347) | [CrossRef Full Text](https://doi.org/10.1016/j.jplph.2016.02.018) | [Google Scholar](http://scholar.google.com/scholar_lookup?&title=Nitric+oxide+is+required+for+hydrogen+gas-induced+adventitious+root+formation+in+cucumber.&journal=J.+Plant+Physiol.&author=Zhu+Y.&author=Liao+W.&author=Wang+M.&author=Niu+L.&author=Xu+Q.&author=and+Jin+X.&publication_year=2016&volume=195&pages=50-58)