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Review

How Hydrogen (H_2) Can Support Food Security: From Farm to Fork

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Abstract: Molecular hydrogen (H_2) is a low-molecular-weight, non-polar and electrochemically neutral substance that acts as an effective antioxidant and cytoprotective agent, with research into the effects of H_2 incorporation into the food chain, at various stages, rapidly gaining momentum. H_2 can be delivered throughout the food growth, production, delivery and storage systems in numerous ways, including as a gas, as hydrogen-rich water (HRW), or with hydrogen-donating food supplements such as calcium (Ca) or magnesium (Mg). In plants, H_2 can be exploited as a seed-priming agent, during seed germination and planting, during the latter stages of plant development and reproduction, as a post-harvest treatment and as a food additive. Adding H_2 during plant growth and developmental stages is noted to improve the yield and quality of plant produce, through modulating antioxidant pathways and stimulating tolerance to such environmental stress factors as drought stress, enhanced tolerance to herbicides (paraquat), and increased salinity and metal toxicity. The benefits of pre- and post-harvest application of H_2 include reductions in natural senescence and microbial spoilage, which contribute to extending the shelf-life of animal products, fruits, grains and vegetables. This review collates empirical findings pertaining to the use of H_2 in the agri-food industry and evaluates the potential impact of this emerging technology.

Keywords: hydrogen; molecular hydrogen; food; food safety; non-thermal food preservation

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1. Introduction

As the global population increases, so do the obligations to provide nutritious sustenance to an ageing population. For this to be achieved, the preservation of fresh produce is critical. Due to such contemporary issues as climate change, chemical pollution, loss of biodiversity and soil erosion, the production, preservation, and distribution of quality foods becomes ever more challenging [1]. Currently, such preservation processes as cooking, drying, pasteurization, refrigeration and sterilisation can make food products more resistant to microbial spoilage and attenuate lipid oxidation, thereby decelerating the natural decomposition and rancidification of produce over time [2]. Although effective, such techniques can be expensive to implement and maintain; there is, therefore, a requirement to develop alternative, ecologically responsible, low cost and sustainable methods of preserving natural produce.

Molecular hydrogen (H_2) is classified as a 'generally regarded as safe' (GRAS) product by the U.S. Food and Drug Administration [3] and is regarded as a food supplement (E949) under part C group I of regulation 1129/2011 in the European Union [4] and U.K [5]. H_2 technologies are at the forefront of modern research, due in part to it being trialled as an efficient and sustainable source of energy [6] and in part to its recognition as an effective antioxidant and cytoprotective compound in health and agricultural science [7,8]. In this regard, H_2 could provide the increased energy required for sustainable food production, storage and distribution while enhancing food security through maintaining the nutritional value and prolonging the shelf-life of produce.

Oxidative stress and subsequent cellular and tissue damage can be caused by numerous factors, including environmental challenges (e.g., drought, pollution, increased soil salinity), human intervention (e.g., fertilisers, insecticides, paraquat) and natural senescence (e.g., cellular deterioration, microbial spoilage). These factors can affect the growth, yield and nutritional content of food [8]. Furthermore, oxidative damage can lead to the rapid deterioration of food quality, resulting in lipid oxidation, discolouration and alterations to both the nutritional profile and flavour of foods [8]. Lipid oxidation, in particular, is a primary consideration for the meat, fish and dairy industries as it affects the sensory attributes and shelf-life of produce [9].

Antioxidants neutralise reactive oxygen and reactive nitrogen species (ROS/RNS, respectively), which can cause oxidative stress and damage to cells and tissues and disrupt essential functional physiological processes, including energy metabolism and the biosynthesis of proteins and peptides [10]. As an antioxidant, H_2 is demonstrated to quench cytotoxic free radicals, enhance endogenous antioxidant capacity and modulate both inflammatory responses (in animals) [11,12] and stress responses (in animals and in plants) [11,13]. Oxidation of biomolecules can also be inhibited with the post-harvest treatment of plant products (e.g., exposure to H_2 gas or treatment with hydrogen-rich water (HRW)). Additionally, exposing dairy products such as butter to H_2 during processing is shown to prevent biogenic amine formation due to microbial spoilage, a phenomenon attributed to the reducing effect of H_2 [14]. The ability of H_2 to traverse biological boundaries is likely to be highly influential, affecting fundamental organelle biochemistry as well as cytosolic reactions, a possible explanation as to why the application of H_2 has been demonstrated to have positive effects in numerous disease models in both plants and animals.

When growing plants or rearing animals, H_2 can be used as an additive to water in the form of HRW or hydrogen-rich nanobubble water (HNW), or as a food or soil supplement in the form of hydrogen-forming magnesium (Mg) or calcium (Ca) powders. Additionally, HRW, HNW and H_2 gas can also be used as a topical preparation on fruits and foliage (Figure 1).

As a gas, H_2 can be used during the dehydration processes of fruits and pulses, for example, and as hydrogen-infused packaging films in modified packaging atmospheres (Figure 1). Such processes are likely to reduce the oxidation of produce and prolong the shelf-life of foods [10]. Furthermore, foodborne pathogens also pose a significant risk to food security; here, H_2 is documented to inhibit the growth of such bacteria as *Escherichia coli*, *Salmonella listeriosis* and moulds [15], potentially reducing the risk of spoilage and foodborne illnesses.

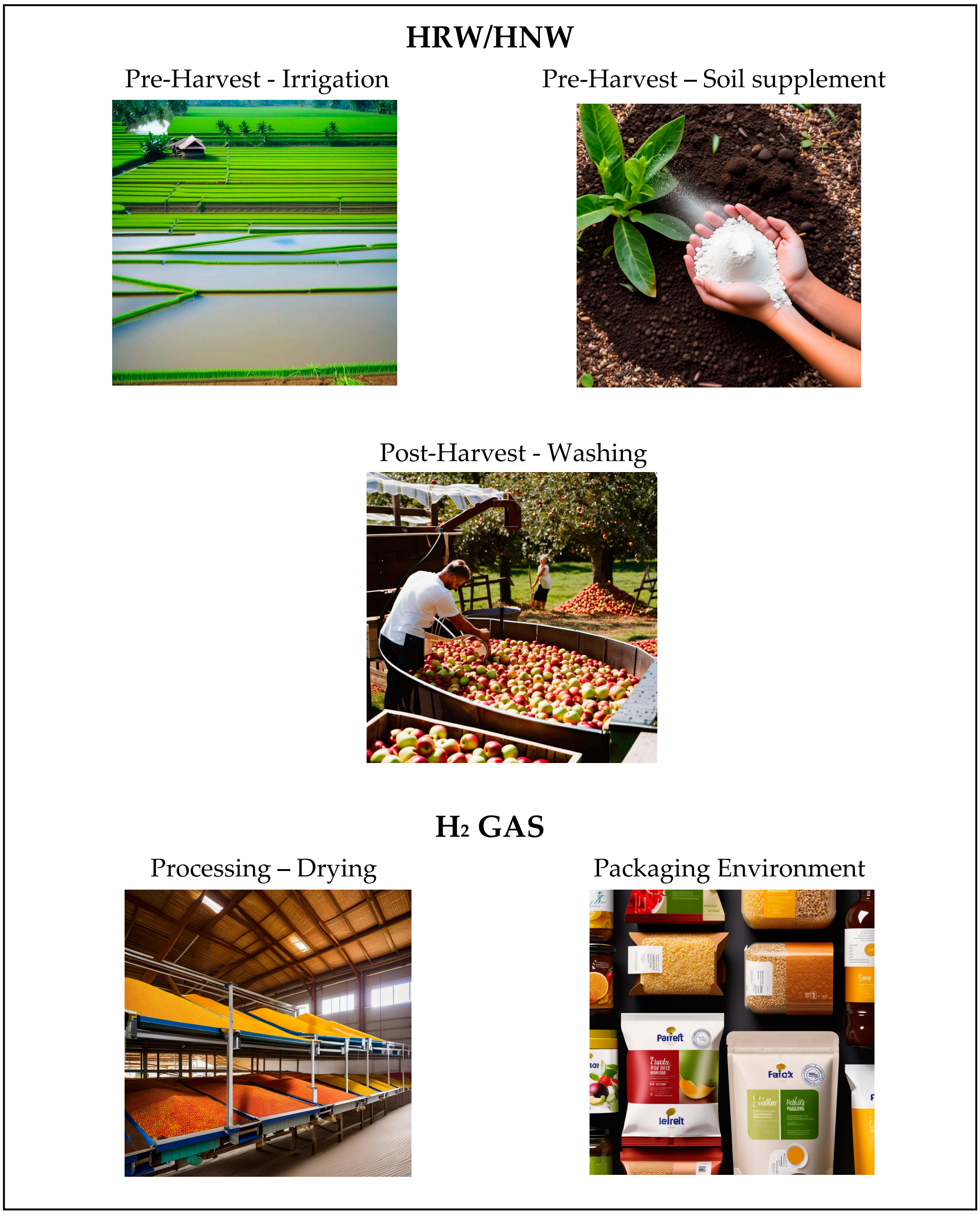

Figure 1. Potential methods of utilizing hydrogen in the agri-food industry. Images created by the author using an artificial intelligence platform (wonderai.app). Mode: Photo. Prompts: HRW/HNW Pre-Harvest Irrigation 'Rice field irrigation'. Soil supplement 'Adding calcium powder to soil'. Post-Harvest 'Washing apples on farm'. H_2 Gas. Drying 'Drying fruit industry'. Packaging 'Dry packaging of food for retail'.

2. H_2 Use on the Farm

Global losses of food productivity as a result of increasing burdens (e.g., climate change, pollution and soil erosion) are estimated to be in the region of USD 170 billion annually [16]. Ergo, there is a pressing requirement for additional, effective, means of preserving the nutritional content, preventing the spoilage and prolonging the shelf-life of fresh produce. In this regard, there is an extensive body of research attesting to the benefits of adding H_2 into the feedwater of seeds, seedlings and maturing plants, wherein H_2, supplied as HRW, is demonstrated to improve crop viability and yield [17,18]. The antioxidant activity of H_2 is proposed to be the primary mode of action, involving the upregulation of glutathione and sulphur metabolism [19], enhanced antioxidant gene expression [18] and promoting hormone synthesis [20]. Such cytoprotective actions proffer resistance to both biotic and abiotic stressors, including drought [21], heavy metal toxicity [17,22], increased salinity [23], temperature variation [18,24] and viral infection [25].

A wealth of academic studies show that exposing plants to H_2 during the germination, plantation and growth phases can enhance root establishment, increase disease resistance and promote the growth and development of leaves, fruits and seeds. Incorporating H_2 into the feedwater of plant crops is a relatively simple process which can be implemented in various ways. For example, HRW and H_2 gas can also be used as a topical application. However, atmospheric losses due to evaporation make it difficult to envisage how practical this application method would be at scale. HRW and HNW can also be obtained by diffusing H_2 gas (formed through water electrolysis) into nutrient solutions and irrigation systems and by dissolving Mg or H_2 donors (e.g., ammonia borane hollow mesoporous silica nanoparticles (AB@hMSN)) in aqueous solutions. Such methods are already being implemented academically [18,20,26] and are beginning to be rolled out commercially.

The addition of H_2 into soil environments is also noted to improve soil quality through increasing H_2-oxidising microbial activity and promoting carbon fixation [27–29], a term referred to as hydrogen fertilisation, although the process is somewhat complex, which may rule out its application in an agricultural setting. Whether this type of application would provide a large-scale, long-term solution to replenishing nutrient-deficient soils will need to be explored.

3. H_2 in the Storage and Distribution Chain

The distribution and storage of fresh produce are paramount to ensuring food security with many aspects (e.g., transportation, warehouse and vendor) reliant on controlling the temperature at which foods are stored. The refrigeration process is not only energy-intensive, costly and environmentally taxing [30], but using this preservation method does not prevent, but mitigates, losses of perishable foods. Therefore, to ensure future food security, it is pertinent to consider novel approaches that can further reduce the deterioration rate of valuable produce.

A broad range of research in animals [11,31,32] and plants [33–35] identifies H_2 as having noticeable reducing properties, which are relevant to the preservation of food products as such redox poise favours a reducing environment, attenuating the accumulative oxidation of lipid components. Lipid oxidation is instrumental in the deterioration of biological substances as it can diminish cell membrane integrity, resulting in ion leakage, dysfunctional organelle activity and aberrant cellular cohesion [36,37]. Preventing lipid oxidation is a leading consideration for increasing the longevity and nutritional value of food products [9,10].

To date, research into H_2 describes the molecule as an effective mediator of cellular homeostasis, albeit the precise mode of action has yet to be delineated. Many reports highlight a direct scavenging effect of such ROS/RNS as the hydroxyl radical ($^{\bullet}OH$) and peroxynitrite ion ($ONOO^-$) [38–40], both significant contributors to lipid oxidation. However, considering the spatial and temporal distribution, and the kinetics of these highly reactive molecules, whether such reactions occur in vivo is questioned [41,42]. Alternative mechanisms of action involving the partial reduction in Fe^{3+} moieties [43] and protein stabilisation [44] have been proposed, and whilst the modality of H_2 is currently a matter of academic debate, what is clear is that implementation of HRW and H_2 gas to post-harvest produce consistently demonstrates an increased resistance to ripening, senescence and spoilage in fruits, herbs and vegetables (Table 1).

Table 1. Identifies the benefits of H_2 application to animal and plant products, noting the mechanism of action and overall effects on fresh produce. APx—ascorbate peroxidase; β-Gal—β-galactosidase; CAT—catalase; Cx—connexin; GR—glutathione reductase; GSH—glutathione; PG—peptidoglycan hydrolase; PL—pectate lyase; PME—pectin methylesterase; POD—peroxidase; SOD—superoxide dismutase.

Product	Application	Process	Mechanism	Outcome	Ref(s)
Banana (*Musa* spp. *AAA cv. Baxijiao*)	HRW (0.4 mM)	26-day storage	Reduced ethylene production and respiratory rate	Delayed ripening	[45]
Chive (*Allium tuberosum*)	H_2 gas (3%)	8-day storage	Increased antioxidant activity APx, CAT, GSH, POD and SOD	Increased shelf-life (100%)	[34]
Kiwi (*Actinidia chinensis*)	HRW (0.6 mM)	16-day storage	Increased antioxidant capacity (SOD) and reduced cellulase, PG and PME activity	Reduced respiration and rotting	[46]
Kiwi (*Actinidia chinensis*)	HRW (0.15 mM)	10-day storage	Increased antioxidant capacity APx, CAT, POD and SOD; reduced activity of β-Gal, Cx, PG, PL and PME	Delayed ripening	[47]
Mushrooms (*Hypsizygus marmoreus*)	HRW (0.1–0.4 mM)	12-day storage	Activated antioxidant activity (APx, CAT, GR, SOD); increased the contents of polysaccharides, protein, total sugar and amino acids	Extended shelf-life	[22,48]
Okra (*Abelmoschus esculentus* L.)	HRW (0.22 mM)	15-day storage	Increased biosynthesis of pectin, hemicellulose and cellulose	Delayed ripening	[49]
Pak Choi (*Brassica Chinensis*)	HRW (0.21 mM)	4-day storage	Delayed chlorophyll degradation; preserved phenolic content	Delayed senescence	[50]
Tomato (*Solanum lycopersicum*)	HRW (0.2 and 0.6 mM)	16-day storage	Prevented nitrite accumulation	Increased vitamin C levels	[51]

In addition to postharvest treatments, preharvest irrigation with HRW has also been demonstrated to protect natural produce against storage-related chilling injury [52]. This indicates that the application of H_2 has long-lasting, positive effects on plant biochemistry. As is shown in Table 1, H_2 has pleiotropic effects in plants, from regulating the activity of endogenous antioxidants including ascorbate peroxidase (APx), catalase (CAT), peroxidase (POD) and superoxide dismutase (SOD) [34], to reducing biomarkers of senescence β-Galactosidase (β-Gal), peptidoglycan hydrolase (PG) and pectin methylesterase (PME) [47] and increasing the biosynthesis of such polysaccharides as cellulose and pectin [49]. It is conceivable that, together, these cytoprotective qualities can further prevent the deterioration of fresh produce in storage and transit.

Incorporation of H_2-producing technologies into established storage and distribution chains will require careful consideration due, in part, to the possibility of igniting H_2 [53], a highly explosive gas, and to the time involved in washing and subsequently drying produce. Additionally, although the preparation of HRW baths is a relatively simplistic process [45,50], with a large volume of produce the process could become labour-intensive. Therefore, it may be prudent to focus on the pre-harvest and processing/packaging applications of H_2.

4. H_2 in Food Processing

A more practical and viable way of treating plant and animal produce can be envisaged during the packaging and processing stages, where H_2 can be applied without much adaptation to current preservation methods. H_2 gas can be easily incorporated into numerous preservation techniques, including drying, fermentation, extraction and preparation of foods (Table 2).

Table 2. The benefits of H_2 addition in the processing of food products. Ca—calcium; K—potassium; Mg—magnesium; Na—sodium. Ile—isoleucine; Leu—leucine; Met—methionine.

Product	Application	Process	Mechanism	Outcome	Ref(s)
Apricot (*Prunus armeniaca* L.)	H_2 gas (4%)	Drying	Increased antioxidant activity	Maintained nutritional profile	[54]
Beetroot (*Beta vulgaris*)	H_2-infused brine (undisclosed concentration)	Fermentation	Increased fermentation-associated microbial content	Reduced biogenic amine formation	[55]
Beetroot (*Beta vulgaris*)	H_2-enriched solvents (ethanol, methanol, water)	Nutrient extraction	Increased extraction yields: antioxidants, flavonoids and phenolics	Sustainable and efficient extraction process	[56]
Lemon (*Citrus lemon* L.)	H_2-enriched solvents (ethanol, methanol, water)	Nutrient extraction	Increased extraction yields: flavonoid and phenolic	Sustainable and efficient extraction process	[57]
Raw butter	HRW 1.6 mg/L	Washing during preparation	Reduced microbial decarboxylase activity; reduced biogenic amine formation; reduced yeast/mould	Improved shelf-life and sensory attributes. Reduced potential for foodborne toxicity	[14,58]
Rice milk	HRW (0.8 mM)	Preparation	Increased essential mineral content (Ca, K, Mg, Na); increased amino acids (Ile, Leu, Met)	Enhanced nutritional profile	[59]
Yoghurt	H_2 gas infusion into pasteurised milk (1 L/min–10 min)	Fermentation	Increased the acidification capacity: *Streptococcus thermophilus* (+10%); increased the reducing capacity: *Lactobacillus delbrueckii* (+13.7%)	Increased microbial fermentation activity	[60]

Dairy products are particularly susceptible to oxidation-related spoilage which can shorten the shelf-life. For example, oxidative reactions in butter lead to the destruction of essential fatty acids and vitamins. The foremost oxidative decomposition products formed in animal-derived produce such as butter are unstable hydroperoxides (R-OOH), molecules which are further decomposed into rancidity-inducing compounds (e.g., aldehydes (R-CH=O), ketones (R-C=O), alcohols (R-C-OH)) [61]. Introducing H_2 in the form of HRW when washing raw butter [58,60] was demonstrated to improve the quality attributes (e.g., acidity, colour), decrease the accumulation of heavy metals, prevent spoilage by inhibiting microbial decarboxylase activity, and retard the growth of yeasts and moulds, prolonging the shelf-life.

Adding H_2 into the preparation stages of such dairy products as butter and yoghurt is shown to inhibit microbial spoilage whilst also promoting microbial fermentation. Similarly, dissolving H_2 gas into the pickling media of vegetable produce was noted to enhance the fermentation process and reduce lactic-acid-bacteria-associated biogenic amine formation. The authors demonstrated that using HRW during the fermentation phase and replacing the medium with freshly infused H_2-enriched brine before pasteurisation was most effective in reducing levels of such biogenic amines as 2-phenylethylamine, putrescine and tryptamine [55]. Dissolving H_2 into solvent fluids used for the extraction of phytochemicals can increase the yields of anthocyanins, flavonoids and polyphenolic substances, whilst in the preparation of rice milk, an alternative to dairy, replacing pure water with HRW increased essential mineral and amino acid content [59].

The use of 4% H_2 gas in the fruit-drying process has also shown an increased potential to maintain the nutritional and sensorial notes of dried fruits [54]. Here, instead of infusing liquids with H_2 generated on demand, a mixture of gases (typically, CO_2, N_2 and H_2) into the drying apparatus is regulated via instrumentation. As such apparatuses utilise gas canisters, and since H_2 is explosive above concentrations of 75% (v/v) [62], increased storage and safety protocols may be required if this mechanism of application is to be exploited in the food preservation industry.

5. Incorporating H_2 in the Packaging Environment of Food

Historically, the packaging of food had the sole intention of providing a physical barrier between the environment and the contents to prevent external contamination. Innovation in the food packaging industry is broadly focused on the incorporation of active components such as ethylene scavengers (e.g., potassium permanganate) into the package, which can maintain, or extend, product quality, sensory attributes and shelf-life [63].

Currently, to improve the quality and longevity of produce, many fresh products are distributed and displayed in plastic packages containing a modified atmosphere composed of carbon dioxide (CO_2) and Nitrogen (N_2) [9]. This O_2-depleted environment inhibits cellular oxidative mechanisms and microbial activity, restricting senescent processes and preserving the contents. However, with compounding stresses on food security and distribution networks, any improvements which can enhance the longevity of fresh produce will be highly valued.

As with the utilisation of H_2 gas in thermal drying discussed previously, incorporating H_2 into the packaging atmosphere should be relatively simple. Nevertheless, unless the gas is used as it is produced, through water electrolysis, for example, the same safety concerns over the storage of pressurised gas and flammability apply. Therefore, stringent safety procedures in food processing and manufacturing environments will be necessary. On the other hand, the benefits of introducing non-explosive (<4% v/v) amounts of H_2 into packaging atmospheres may well outweigh any required investment in safety measures.

Although the precise mechanisms behind H_2 activity in cells have yet to be elucidated, the ability of H_2 to act as an effective antioxidant in plants and produce is now well-documented [8,64–66]. One of the primary functions of H_2 utilization in both agricultural and clinical settings is as an antioxidant, first demonstrated by Ohsawa et al. (2007), in a rodent model of ischemia/reperfusion injury [38]. The highly influential study describes the selective reduction in the highly reactive $^{\bullet}OH$ radical and $ONOO^{-}$ molecules, but no reduction in the important signalling molecules hydrogen peroxide (H_2O_2) and nitric oxide ($NO^{\bullet}$). Either as a result of, or in addition to, selectively neutralising the most detrimental reactive oxygen/nitrogen species, the upregulation and increased expression of such antioxidant proteins and peptides CAT, nuclear erythroid factor-2 (Nrf-2) and SOD are often reported [34]. Upregulation of such endogenous antioxidants is known to enhance tolerance to such environmental stressors as diseases, salinity, drought and temperature stress, and to confer a level of microbial resistance [23–25]. Such antioxidant activity is also demonstrated when H_2 is incorporated into the packaging atmosphere. Recently, several studies have identified that adding up to 4% H_2 gas into such packaging environments can markedly improve both the sensory qualities and shelf-life of fresh produce (Table 3).

Table 3. Identifies the benefits of H_2 application in the processing and packaging of fresh produce.

Product	Application	Mechanism	Outcome	Ref(s)
Cheese	H_2 gas (4%)	Reduced mesophilic-aerobic bacteria; reduced yeast-mould	Improved shelf-life	[67]
Eggs	H_2 gas (up to 3%)	Inhibited microbial spoilage; maintained antioxidant capacity; reduced pH (yolk and white)	Improved shelf-life	[68]
Freshwater Fish: Rainbow trout (*Oncorhynchus mykiss*)	H_2 gas (4%)	Reduced microbial decarboxylase activity; reduced biogenic amine formation; reduced protein degradation	Improved shelf-life Reduced potential for foodborne toxicity	[6]
Seawater Fish: Horse mackerel (*Trachurus trachurus*)	H_2 gas (4%)	Reduced microbial decarboxylase activity; reduced biogenic amine formation	Improved shelf-life; reduced potential for foodborne toxicity	[6]
Shrimp (*Fenneropenaeus chinensis*)	H_2 gas (up to 1%)	Reduced lipid oxidation and purine metabolism	Improved shelf-life and sensory attributes	[69]
Strawberries (variety undisclosed)	H_2 gas (4%)	Increased phenolic and anthocyanin content	Increased shelf-life (300–500%)	[70]

It can be seen from Table 3 that the addition of H_2 in the packaging atmosphere of animal and animal-derived products, including cheese, eggs and fish, was able to inhibit both lipid oxidation and the decomposition of amino acids by decarboxylase enzymes, whilst concomitantly reducing microbial growth and spoilage. As with the pre-harvest and processing applications of H_2 (Tables 1 and 2, respectively), the preservation of endogenous antioxidant activity may account for many of the effects noted in Table 3. Furthermore, in addition to being utilised as a preservative gas, H_2 gas can be used to detect flaws in food packages such as mis-sealing, tears, and small holes [71]. Here, the gas is used during the sealing process, before the packet passes through a sensor; if the sensor detects H_2, an alarm is activated, allowing for the damaged packet to be removed from the production chain and repackaged before wastage occurs.

Although supplementary research into the use of H_2 gas in the packaging environments of perishable goods is warranted, the initial findings strongly suggest that such reducing-atmosphere packaging environments can impede the natural deterioration of fresh produce. However, before this method of preservation can be adopted by the agri-food industry, detailed cost-benefit analyses, assessments of the practical incorporation into working spaces (e.g., safety, storage, transportation) and the effects of H_2 on other food products will be required.

6. Safety

Using H_2 safely will require proper handling precautions and procedures due to its flammability and potential for explosive reactions. For example, during storage, H_2 will need to be contained in appropriate cylinders in well-ventilated areas away from heat sources, ignition and direct sunlight [72], a factor that is likely to pose an issue towards comprehensive use, particularly in countries such as the UK and USA which have stringent safety policies. Cylinders should also be regularly checked for damage to reduce the potential of leakage. Additionally, as H_2 is lighter than air, proper airflow and ventilation are also necessary to prevent the accumulation of H_2. Equipment, fittings and connections of any apparatus using H_2 will also require detectors/monitors, which can provide early warning of malfunction and H_2 leakage. Pressure regulators and flow meters can detect sudden pressure changes and may well be instrumental in preventing harm from faults in H_2-associated equipment. It will be prudent to ensure individuals working with H_2 are adequately trained in the safe handling, storage and emergency procedures, with training to include recognizing the potential hazards and how to respond to incidences that may involve H_2 (e.g., evacuation, fires, leaks, etc.).

7. Future Perspectives and Conclusions

Reducing food waste and cutting costs is a primary concern for food security and the agri-food industry [73,74]. To better assess the potential for H_2 to support food growth, distribution and production industries, large-scale, in-field research, along with further empirical investigations into the primary, secondary and, perhaps, tertiary effects of H_2 applications will be advantageous. It may also be prudent to analyse whether heritable traits are affected by long-term H_2 usage. This could involve understanding the epigenetic context, hormone regulation, and resistance to biotic and abiotic stressors.

Recent studies, such as the one conducted by Cheng et al. (2021), have identified that HNW is suitable for irrigating crops [17]; therefore, it may be propitious to focus on this aspect of H_2 production when considering pre-harvest administration. For post-harvest applications, comparative analyses of whether treatment with HRW/HNW or H_2 gas, and at what stage in the distribution chain application is most effective, would be beneficial.

It is not only the efficacy of hydrogen treatments that must be scrutinised, but the cost-effectiveness, sustainability and long-term benefits of treatment must also be assessed. The cost of established 'green' hydrogen production technologies has been estimated to be 0.7–1.4 GBP/W for alkaline water electrolysis and 0.8–2.2 GBP/W for proton exchange membrane (PEM) electrolysis [75,76]. However, as such production costs are influenced by commercial innovation and investment, and the interest in H_2-producing technologies is growing internationally, it is likely such costs will be reduced as H_2 technology becomes more efficient over time. In addition to the purchase and maintenance costs, an assessment of the durability and longevity of commercial units versus conventional treatments and processes will also need to be considered.

To summarise both the risks and benefits of commercial H_2 usage in the agri-food industry, Table 4 provides an analysis of the strengths, weaknesses, opportunities and threats (SWOT) for incorporating H_2 into the agri-food chain.

Table 4. A SWOT analysis of strengths, weaknesses, opportunities and threats to incorporating H_2 into the agri-food chain.

	Strengths	Weaknesses	Opportunities	Threats
HRW/HNW				
Irrigation	Can be used in multiple stages of plant development (Germination, Growth) Low maintenance Measurable dosing	Retention of H_2	Agriculture Horticulture Floriculture	Unknown costs for large-scale implementation
Topical	Can be used pre- and post-harvest May reduce post-harvest spoilage	Possibly labour-intensive	Agriculture Horticulture Floriculture	Possibly difficult to implement Unknown commercial efficacy
H_2 Gas				
Drying	Can be used with a wide range of products Relatively easy to incorporate into established processes	Should not be used with high-temperature food preservation methods Should not be used near sources of ignition	Food manufacture and processing	Requirement for increased safety and storage protocols Unknown costs for large-scale implementation
Packaging	Can be used with a wide range of products Measurable dosing Relatively easy to incorporate into established processes	Should not be used near sources of ignition	Food packaging	Requirement for increased safety and storage protocols Unknown costs for large-scale implementation
Soil Supplement	Low maintenance	Unknown H_2 levels	Agriculture Horticulture Floriculture	Unknown long-term effects of bi-products on soil composition

In conclusion, via regulating antioxidant, hormonal and microbial activity, a wealth of evidence is accumulating strongly indicating that H_2 may be an effective fertiliser, microbial deterrent and preserving agent for edible produce (Tables 1–3). The application of H_2, whether as an atmospheric gas or in solution, into the agri-food industry may help to support the healthy growth of plant produce, increasing biomass, resistance to stress and yield (Table 1). Adopting the hydrogen strategy in various stages of the food production chain can decrease the heavy metal content, limit the biogenic amine formation of food products, preserve the nutritional and sensory properties, and extend the product's shelf-life [4,6,17,22]. Furthermore, reduction in both animal-derived and plant-derived food wastage can be achieved through H_2-induced inhibition of endogenous senescent processes (Tables 2 and 3). Moreover, as a sustainable, non-toxic and non-polluting agent, the future of H_2 application in the agri-food industry could help to reduce the carbon footprint, from the field to the table, of such a demanding supply chain.

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Abbreviations

APx—Ascorbate peroxidase; β-Gal—β-Galactosidase; CAT—Catalase; Cx—Connexin; GR—Glutathione reductase; GSH—Glutathione; GRAS—Generally regarded as safe; HNW—Hydrogen-rich nanobubble water; HRS—Hydrogen-rich saline; HRW—Hydrogen-rich water; Nrf2—Nuclear erythroid factor-2; PEM—Proton exchange membrane; PG—Peptidoglycan hydrolase; PL—Pectate lyase; PME—Pectin methylesterase; POD—Peroxidase; RNS—Reactive nitrogen species; ROS—Reactive oxygen species; SOD—Superoxide dismutase; USD—United States dollar.

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