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Comprehensive review on the current scenarios in onion processing and addressing the grand onion challenge of India

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ABSTRACT

Onion (*Allium Cepa* L.) is an economically important bulbous crop and finds applications as food, flavor, and nutraceutical ingredient. The health benefits associated with onions can be attributed to the presence of organosulphur compounds, polyphenols, and prebiotics. India is one of the largest producers of onion and contributes to nearly 25% of the world's production. Onion is highly perishable and susceptible to post-harvest losses such as rotting, sprouting, and weight loss, which combinedly contribute to nearly 23% - 25% of total crop loss in India. This can be attributed to weather abnormalities and a paucity of effective storage systems (cold storage) leading to crop loss and subsequently high degree of price volatility. Apart from existing technologies, novel techniques such as ozonation, gamma irradiation, and cold plasma have been considered for the decontamination of onions and enhancement of the shelf life. In this paper, a comprehensive review of the nutraceutical properties of onions and various techniques involved in onion harvesting and storage along with the factors affecting their shelf life is discussed. Further, we have compiled information on the existing and novel techniques that are currently explored for enhancing the shelf life and value addition of onions and reviewed the impact of processing on the nutritional quality of onions. Valorization of wastes generated from onion processing for the production of high-value products such as nutraceuticals and biofuels would enhance the sustainability of the industry. Further integration of volatilomics for the detection of spoilage and contamination in onions would augment real-time quality control and reduce post-harvest losses and stabilize the price volatility.

1. Introduction

The *Allium* genus contains a variety of species, of which is *Allium cepa* L., commonly known as bulb onion is commercially one of the most important crops with huge applications in food, flavouring and nutraceutical industries. Utilization of onions in food and medicine are since ancient times and there are several records dating back to 2700 BC from the old kingdoms of Egypt and Sumeria. Even older accounts, from about 4000 BC, can be found in Indian literature such as Ayurveda (Hanelt, 2018) suggesting that onions have been domesticated way back from 4000 BC for culinary and medicinal applications across the cultures (Kabrah, 2015). Although several species of *Allium* are consumed worldwide such as *Allium sativum* (garlic), *Allium ampeloprasum* L., (leek), *Allium fistulosum* L., (Welsh onion), *Allium schoenoprasum* L., (chives) and *Allium semenovii*, bulb onion is the widely cultivated crop (Alam et al., 2023; Kumar & Kumar, 2023). In addition to being consumed fresh, onions are utilized in many processed forms such as dehydrated flakes, paste and powders in packaged foods (Manohar et al., 2017). Bulb onions are second most widely cultivated crop next to tomato with a global production of 106.59 million metric tonnes (MMT)

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contributing to 9% of the global crop production (FAO, 2021). Almost 175 countries in the world grow onions, with India (26.4 MMT), China (24.16 MMT), USA (3.10 MMT), Egypt (3.31 MMT) and Turkey (2.5 MMT) being the top five producers (Stoica et al., 2023).

The potential health-promoting applications of onion are mainly attributed to phytochemicals present in them such as phenolic acids, flavonols, anthocyanins, and more importantly organosulphur compounds and thiosulfates (Slimestad et al., 2007; Bora & Sharma, 2009; Alam et al., 2023; Kumar & Kumar, 2023). The unique aroma and pungent flavour of onions are attributed to the presence of organo-sulphur compounds such as allin, isoallin, S-allyl-L-Cysteine (Velisek et al., 2006; Bora & Sharma, 2009; Saviano et al., 2019). These phytochemicals are responsible for the myriad health benefits such as anti-inflammatory, antimicrobial, anti-cancerous, cardio- and hepatoprotective properties (Griffiths et al., 2002; Kyung, 2012; Sagar et al., 2022; Kumar et al., 2022). Further, phytochemicals from onions have been reported to possess antitumor activity, and are being explored for cancer prevention and therapy (Bahram-Parvar & Lim, 2018). Among the different secondary metabolites, quercetin derivatives, mainly quercetin glucosides are of high significance and attributed with several of the aforesaid health benefits (Cattivelli et al., 2021). Onions have been ranked the highest in quercetin concentration among 28 different vegetables (Manohar et al., 2017). With its unique flavour and enormous health benefits, onions fetch a huge demand in the global trade.

Despite being a commercially important crop, onion production and processing sector is highly volatile owing to its susceptibility to post-harvest losses such as rotting (10-12%), sprouting (8-10%) and weight loss (30-40%) during the storage, causing significant economic losses (Tripathi & Lawande, 2015; Rawal & Verma, 2020). In India, nearly 35% of the crop is lost due to above factors mainly due to the improper supply-chain and a paucity of efficient storage systems (Kumar et al., 2007). Conventional practices for reducing postharvest losses include drying of harvested onion bulbs, chemical treatments and cold storage (Muhie, 2022). However, the presence of chemical residues and associated health issues have driven development of novel, physical and non-thermal processes such as ozonation, gamma irradiation, cold plasma and bio-fumigation for enhancing the shelf life of bulbs (Savitha, 2021; Allai et al., 2023). However, these technologies are still far from commercial adoption. In India, the onion prices show a seasonal fluctuation and the wholesale rate per quintal (100 kg) vary from INR 800 to INR 5000 especially during offseason, which severely impact domestic consumption and export market (Birthal et al., 2019). Adoption of effective post-harvest technologies have been advocated for the reduction of the price volatility in onions (Sisodiya et al., 2011; Ghanghas et al., 2017; Yeshiwas et al., 2023). With India being the global leader in onion production, it becomes important to understand the various aspects such as production, post-harvest management and value addition of onions. In this context, the present paper offers a comprehensive review on various aspects of onion crop including its phytochemical composition, traditional medicine and therapeutic properties with respect to Indian traditional knowledge systems, production statistics and characteristics of commonly cultivated onion varieties and their harvesting. Further the paper succinctly describes the various problems associated with onion cultivation and post-harvest losses (rotting, weight loss, sprouting and rooting) and their mitigation strategies. A section on recent (novel) techniques in the post-harvest management of onion such as cold-plasma, ozonation, and gamma irradiation is discussed with case studies. Emphasis on different value-added processing techniques and their impact on the nutritional quality of onion products is described.

Further, onion processing generates significant quantities of waste such as peel, pomace, roots and leaves including pseudostems which possess bioactive and functional compounds such as anthocyanins, flavonoids and polysaccharides (Sagar et al., 2022; Stoica et al., 2023). Approximately 37% of the of fresh onions produced are discarded as processing waste globally. It has been estimated that nearly 500,000 tons per year of onion process waste are generated in Europe (Zhang et al., 2024); while in the USA, the wastage stood at 381,000 tons (USDA-NASS, 2023). There are no clear statistics with respect to generation of onion waste in India. However, Salunkhe et al. (2022) reported that approximately 300 to 500 kg per day of onion waste is generated per day in India amounting to 90-150 tons per year. Valorisation of the aforesaid processed waste for the production of high value products such as natural colours, nutraceuticals, functional polysaccharides and bioethanol would enhance the sustainability of the onion processing industry. In this direction, the present review has summarized different process routes for effective utilization of onion wastes. Lastly, the paper discusses the integration of some futuristic technologies such as image processing techniques, volatilomics and flavoromics for detecting contamination and spoilage in onions and to enhance the real-time quality control and monitoring of onions during storage thereby reducing the post-harvest losses. In summary, the paper aims to provide a comprehensive view on various aspects of post-harvest management of onion crops, ensuring a continuous supply and stabilizing price volatility in India.

2. Major phytochemicals and health benefits of onion

2.1. Onion phytochemicals

Onions are a rich source of phytochemicals which are responsible for its unique aroma and clinically proven therapeutic properties. Some major classes of bioactive metabolites present in onions are polyphenols, organo-sulphur compounds, organic acids and prebiotic compounds such as fructo-oligosaccharides (Sagar et al., 2022). The major class of polyphenols present in the onions are flavonols, anthocyanins, and the dihydro flavonols (Slimestad et al., 2007). Nearly 25 different flavonols have been characterized in different onion varieties with quercetin derivatives being the predominant ones. The concentration of quercetin varied greatly with different type of onion varieties, such as, between 18.5 and 63.4 mg 100 g FW^{-1} in white onions, 5.4 and 28.6 mg 100g FW^{-1} in yellow onions and between 2.2 and 89 mg 100g FW^{-1} in red onions (Rodrigues et al., 2010). The quercetin derivatives are mostly present in the glycosylated forms, exclusively glucose molecules, attached to the 4′, 3, and/or 7-positions of the aglycones and quercetin 4′-*O*-glucoside (Slimestad et al., 2007) and quercetin 3,4′-diglucoside are the most reported ones constituting nearly 90% of the total flavonols (Lombard et al., 2002; Cattivelli et al., 2021). Similar derivatives of other flavonols such as kaempferol, myricetin and isorhamnetin have been detected in minor quantities in onions (Ren et al., 2020).

The other predominant class of flavonoids responsible for wide range of colour shades in onions are anthocyanins. The anthocyanin content ranged between 0.75 and 30 mg 100 g FW^{-1} with highest anthocyanin content observed in red onions (Zhang et al., 2016). Anthocyanins are primarily concentrated in the outer epidermis (shell or skin) of the onions followed by inner layers and least in the edible portions (Samota et al., 2022). Anthocyanins exist mostly in the glycosylated forms with glucose as major sugar moiety followed by arabinose. In addition, anthocyanins are acylated/ acetylated with aliphatic acids, mainly malonic acid (Slimestad, et al., 2007). Cyanidin 3-glucoside was identified to be the major class of anthocyanins in onions, specifically cyanidin 3-(6′’-malonyl) glucoside contributing to 45-55% of the total anthocyanin content (Rodrigues et al., 2010; Pérez-Gregorio et al., 2014). The other minor anthocyanins detected in onions are peonidin-3-glucoside, delphinidin-3-glucoside and petunidin and pelarogonidin-3-glucoside (Samota et al., 2022). The other major class of flavonoids are dihydroflavonols mainly constituted by taxifolin glucosides (Slimestad et al., 2007). The onions contain both hydroxy cinnamic (HCA) and hydroxy benzoic acids (HBA) classes of phenolic acids. The total phenolic acid content (TPC) in onions range between 60.65 to 96.22 mg 100g FW^{-1} (Zhou et al., 2020). Among the HCAs, ferulic acid, sinapic acid, p-coumaric acids and caffeic acid are predominant while in HBAs gallic acid, protocatechuic acid and syringic acids were the major ones (Sagar et al., 2022; Chakraborty et al., 2022).

2.2. Aroma compounds of onion

Onions are known for their unique pungent aroma attributed to the presence of organo-sulphur compounds (OSCs) in both volatile and non-volatile fractions of the onion bulb. The predominant non-volatile OSCs are S-alk(en)yl substituted cysteine sulphoxides and the γ-glutamyl peptides constituting nearly 1% - 5% of dry weight (Velisek et al., 2006). The major S-alk(en)yl substituted cysteine sulphoxides are (+)-S-methyl-, (+)-Spropyl-, trans-(+)-S-(1-propenyl)-L-cysteine sulphoxides and cycloalliin (Bora & Sharma, 2009). The concentration of OSCs varied across the varieties and the developmental stage of the plant. Loredana et al., (2019) reported that organo-sulphur compounds present in onion ranges from 96.39 to 139.32 mg 100 g DW^{-1}.

The pungency and lacrimatory properties of onion is attributed to the presence of volatile OSCs. When the onion bulbs are cut or crushed, an enzyme mediated mechanism of OSC biosynthesis is initiated (Nock et al., 1987; Bora & Sharma, 2009). When the cells are broken, S-alk(en)yl substituted cysteine sulphoxides (precursors of volatile compounds) comes in contact with alliinase enzyme and produces different sulfenic acids, ammonia and pyruvate (Saviano et al., 2019).These sulfenic acids are highly unstable and immediately react with other molecules to form (Z)- propanethial-S-oxide that have lacrimatory properties which further dimerizes to form (Z,Z)-d,l-2,3-dimethyl-1,4-butanthiol-S,S'-dioxide (allicin analogues) (Bora & Sharma, 2009). The thiosulphinates are further converted to thiosulphonates, thiophenes, mono and disulphides and disulphide molecules such as zwiebelanes, alpha-sulphinyl disulphides such as cepaenes (Corzo-Martínez et al., 2007). Further, the volatile fractions, mainly the essential oils are composed of alk(en)yl sulphides such as dipropyl disulphide (21% to 60%), dipropyl trisulphide (17% - 21%), methyl 5-methylfuryl sulphide (~18%) and methyl propyl trisulphide and methyl 1-propenyl disulphide (7% - 15%) (Vazquez-Armenta et al., 2016). The major phytochemicals and aroma compounds distributed in the onion is represented in the Fig.1.

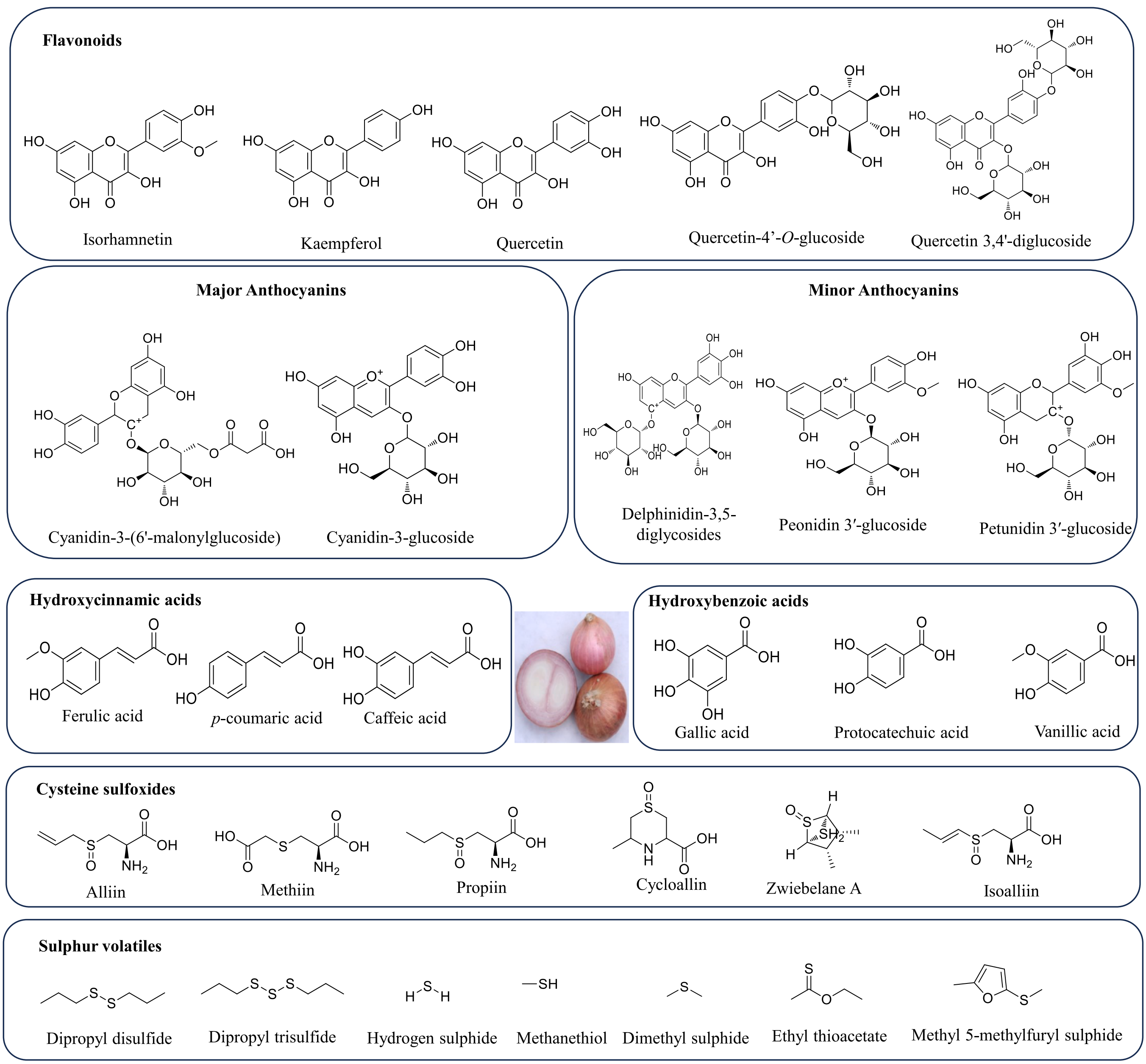


Fig. 1. Various metabolites of onion.

2.3. Health benefits of onion

Onions have been attributed with myriad health benefits including anti-inflammatory, anti-cancer, antioxidant, cardio-protective, neuro-protective, hepato-protective, wound healing and immunomodulatory properties (Sagar et al., 2022). Several human supplementation studies have validated the health benefits of onions. In a study conducted by Puccinelli et al., (2017) the organo-sulphur compounds present in onions such as diallyl trisulphide (DATS) triggered cancer cell cycle arrest at the G2/M phase and reduced the risk of gastric cancer. Further, the polyphenol extracts of onions have been reported to inhibit phosphatidylinositol 3-kinase (PI3K)/Akt signalling pathway, thereby reducing the mitochondrial membrane potential, and initiating the caspase-dependent apoptosis in cancerous cells (Lee et al., 2014). The strong antioxidant capacity of onions can be attributed to their ability to regulate the oxidative stress by quenching the reactive oxygen species (ROS), free radicals and increasing the activity of intra-cellular antioxidant enzymes like glutathione (GSH), superoxide dismutase (SOD) and catalase (CAT) and overall cellular antioxidant levels (Law et al., 2016; Omar et al., 2020).

Further, consumption of onion and its aerial parts decreased the insulin resistance in patients by reducing the high blood sugar levels along with regeneration of β-cells of pancreas (Baragob et al., 2015; Jafarpour-Sadegh et al., 2017). Supplementation of quercetin rich onion juice increased the LDL receptor mRNA expression and synthesis of bile acids which improved cholesterol metabolism in the human blood circulation (Lu et al., 2015). Onion extracts minimized the risk of obesity by enhancing the respiration process in the adipocytes which helps in decreasing total body fat (abdominal visceral fat), reduced blood triglyceride levels and C-peptides (Jeong et al., 2020).

Apart from these, onions have been shown to possess cardioprotective properties by virtue of its ability to modulate omega 3: omega 6 ratio and increase the PUFA levels in erythrocytes (Zhao et al., 2017; Jeong et al., 2020; Choi et al., 2020;). In another case study, Brüll et al. (2015) reported lowering of ambulatory blood pressure (AMB) by the quercetin enriched extracts of onion peels. Cardiac health is always related to total cholesterol levels, oxidative stress and inflammatory cytokines in the body (Hertiš Petek et al., 2022). In another study, Chiu et al. (2016) soaked the chopped onions in red wine for 8 days and then grinded the soaked onions and used the filtered extracts, termed red wine extract of onion, as nutraceutical supplement. Supplementation of 125 ml of red wine extract of onion to hypercholesterolemic healthy subjects (with total plasma cholesterol > 180 mg dL^{-1}) resulted in the reduction of total cholesterol (TC) and LDL cholesterol levels, and improved the antioxidant capacity of the cells when compared to red wine supplementation alone. The enhanced antioxidant activity was attributed to the increased activity of glutathione reductase (GR) and glutathione (GSH) and reduction in the inflammatory marker (Factor VII) levels (Chiu et al., 2016).

Other health benefits of onion include hepatoprotection and improvement of neurological functions. Dehydrated onion powder has been reported to down-regulate the expression of hepatic TNF-α gene and decrease levels of alanine aminotransferase in various animal models indicating its strong hepatoprotective capability (Emamat et al., 2018; Nishimura et al., 2019). Similarly, onion extracts have been reported to improve neural-muscle coordination and memory deficits. Further they reduced reactive oxygen levels (ROS), and acetylcholinesterase (AChE) activity and decreased the aluminium deposition in the brain (Singh & Goel, 2015). Furthermore, onion bulb extracts demonstrated wound healing properties by inhibiting vascular endothelial growth factor (VEGF) production which is the major cause of hypertropic scars and keloids in burn patients (Campanati et al., 2021).

Onions possess immunomodulatory and anti-infectious properties. The flavonoids and OSCs present in ethanolic extracts of onions reduced the secretion of pro-inflammatory cytokines (IL-6, TNF-α, and IL-1-β) and enhanced the phagocytic activity of cells (Marefati et al., 2021). Further the onion flavonoids activated the detoxifying enzyme (GST) which modulates the inflammatory mechanisms inside the cells (Suleria et al., 2015; Marefati et al., 2021). The immunomodulatory potential of onion was further demonstrated by Prasanna & Venkatesh, (2015) who reported that onion lectin (*Allium cepa* agglutinin) increased the production of Nitric oxide (NO), pro-inflammatory cytokines (INF-γ, IL-6) and induced a Th1-type immune response when the cells are exposed to infections. Health benefits of onion are presented in Fig. 2

2.4. Fructo-oligosaccharides and prebiotic properties of onion

In addition to flavonoids and organo-sulphur compounds, onion bulbs contain non-structural carbohydrates that include reducing sugars such as fructose and glucose, as well as oligosaccharides also known as fructans. These carbohydrates account for approximately 60–80% of the DM content with fructans constituting nearly 50% of the total non-structural carbohydrates content (Jaime et al., 2001). According to the food central database of the United States Department of Agriculture (USDA), the total carbohydrates constituted 9.34 g 100 g^{-1} F.W. of bulbs with sugars constituting nearly 50% of the total carbohydrates (4-5 g 100 g^{-1} F.W.). Among the identified sugars, monosaccharides were predominant and two folds higher, with glucose (0.99-2.34 g 100 g^{-1} F.W.), fructose (0.7-1.85 g 100 g^{-1} F.W.) being the abundant constituents (https://fdc.nal.usda.gov/fdc-app.html#/food-details/170000/nutrients). Disaccharides such as sucrose constituted between 0.5 and 2.04 g 100 g^{-1} F.W. The prebiotic property of onions can be attributed to the presence of fructans, mainly fructo-oligosaccharides (FOS) and inulin. Both inulin and FOS are composed of linear chains of fructose units, linked by β (2–1) bonds and often terminated by a glucose unit (Bruggencate et al., 2004). The total fructans (inulin-FOSs) range from 3.7 to 4.5 g 100 g-1 F.W of onion bulbs (Kumar et al., 2015; Aisara et al., 2021). Onion bulbs contain three types of FOS *viz.*, tri-, tetra and pentasaccharides of fructose corresponding to kestose (GF2), nystose (GF3) and fructofuranosylnystose (GF4). Although higher degree of polymerization was observed, the trisaccharide fraction (GF2) was the predominant one. FOS were mainly located in the inner parts and outer two fleshy layers of the bulbs (Jaime et al., 2001). In a study by Aisara et al. (2021), inulin-FOS was determined at 74±2.8 g L^{-1} of onion juice. Consumption of FOS derived from onion increased the abundance and diversity of probiotic strains like *Bifidobacterium,* and *Lactobacillus* and butyrate-producing microbial strains such as *Faecalibacterium, Ruminococcus* and *Oscillospira* (Tandon et al., 2019; Aisara et al., 2021). Butyrate is a short-chain fatty acid (SCFA) produced due to microbial activity in the gut by probiotic anaerobic bacteria. Water extracts of onion have been reported to possess prebiotic properties by altering the gut microbiota structures and enhancing the metabolite production such as SCFAs mainly butyrate and indole derivatives in the gut by promoting the growth of probiotic strains (Yoo et al., 2025). Butyrate possesses an important role in the glucose homeostasis, lipid metabolism, and suppressing the gut inflammation (Zhang et al., 2023). Butyrate exhibits a wide range of health benefits ranging from anti-inflammatory, anti-obesity, antioxidant and anti-cancerous and known to modulate metabolic pathways (Chen et al., 2020; Amiri et al., 2022). Thus, onion derived extracts could be targeted and positioned as prebiotics for healthy gut.

2.5. Traditional medicinal and therapeutic knowledge on onion

Onion is one of the oldest known vegetables which has been part of human diet and traditional medicine dating back to 4000 years (Charles, 2012). In India, the usage of onion is mentioned in Ayurvedic texts such as *Charaka Samhita* dating back to 6th century BC (Ekşi et al., 2020). Onions are widely used in traditional medicine systems like Ayurveda, Unani and Siddha, collectively known as AYUSH system of medicine (AYUSH- Ayurveda, Yoga, and Naturopathy, Unani, Siddha and Homoeopathy) for the treatment and prevention of various ailments.

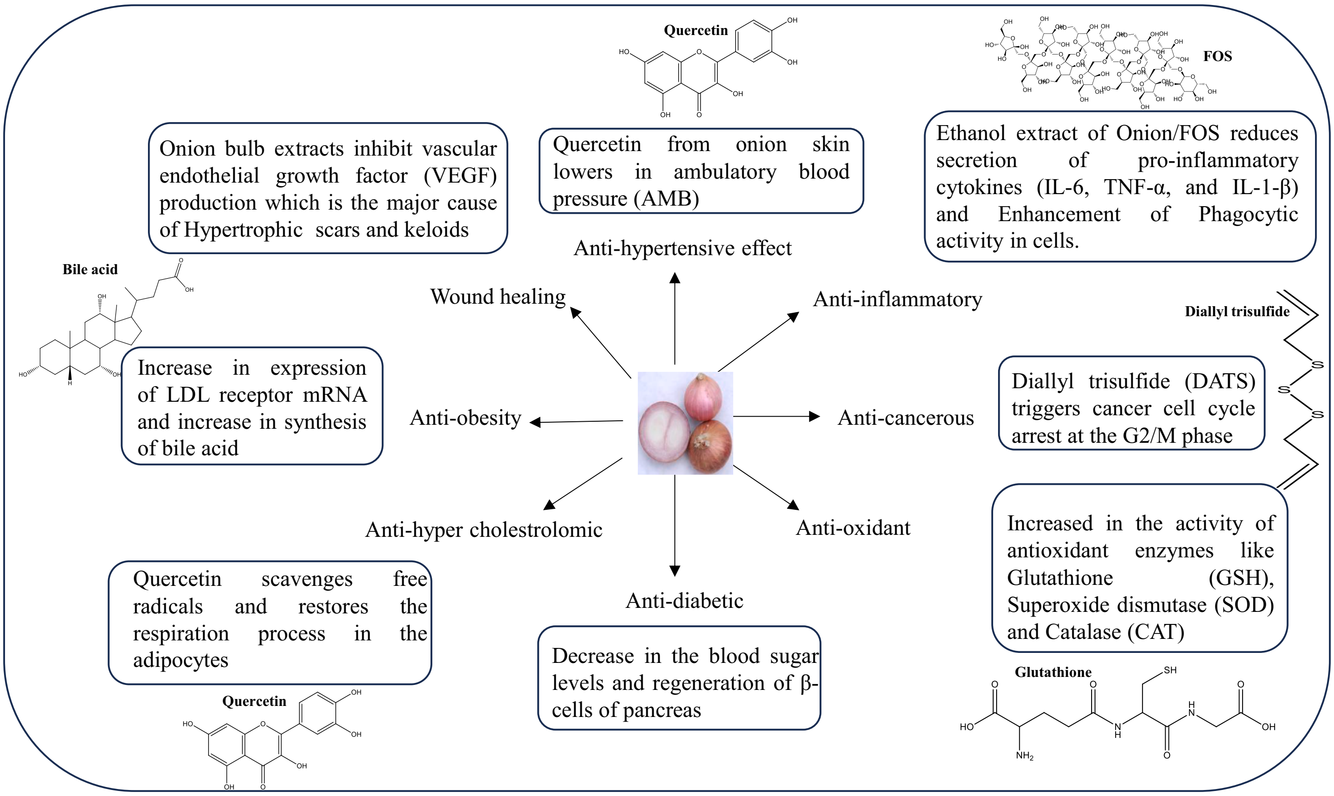


Fig. 2. Various health benefits of onion.

The Council of Scientific and Industrial Research-Traditional Knowledge Digital Library (CSIR-TKDL) has compiled and hosts a digital database on various traditional medicines (https://www.tkdl.res.in/). Database search with keyword "onion" indicated 11 different formulations containing onion. In the Ayurvedic text, *Charaka Samhita* onion has been mentioned as a remedy for aggravating *kapha dosha* (spleen damp) and alleviating *vata dosha* (liver wind). Further it is reported that onions are useful component of diet, promoting strength and act as aphrodisiac. According to Ayurveda, onion bulbs can be used for treatment of various ailments such as *Jirnajawara* (chronic fever), *Krmiroga* (parasitic infections), *Gulma* (thoraco-abdominal tumors), *Kustha* (psoriasis), *Medoroga* (obesity), *Yonivyāpata* (gynaecological problems such as dysmenorrhea), *Śūla, Karnaśūla* (colitis, abdominal pain), *hrdroga* (heart disease), *visamajawara* (irreregular fever) (Akbar, 2020)

Siddha, another Indian origin traditional medicine system prevalent in the southern part of the India mentions onion as an important ingredient in several classical text book such as *Bogar 700* and *Agathiar vaithia rathna churukkam 300* (Subbarayappa, 1997; Wilson et al., 2007). *Kalingathi ennai,* a siddha formulation containing onion juice is used for infertility, treatment of polycystic ovarian syndrome, disorders of menstruation, and diseases of female genital organs (Brunda et al., 2018). Formulations prepared using onion are commonly used for treatment of haemorrhoid (Esakkimuthu et al., 2018). *Vizhuthi Ennai*, a polyherbal formulation consisting onion juice is administered generally for the treatment of pregnancy related disorders, dysmenorrhoea, worm infestation, pain, convulsions, and infertility (Thirumalai et al., 2021). A study conducted by Jeje et al. (2021) has supported these claims where administration of onion juice modulated the menstrual cycle, reduced the ovarian malonaldehyde (MDA) levels, oestrous length and diestrous frequency as well as increased the activity of ovarian antioxidant enzymes such as ovarian catalase and superoxide dismutase (SOD) along with serum 17β-oestradiol levels. *Moolathirku Thylam* is another siddha formulation used for flatus of piles and it was reported that onion roots possessed anti-hemorrhoidal activity (Alege et al., 2022). Further, onion has been used in several formulations such as *Naga Parpam* which is administered during tubercular cough or cough due to weakness or emaciation, tuberculosis or bronchitis (Rameshkumar & Balasubramanian, 2020). Clinical studies have demonstrated the ability of onion extracts to mitigate tuberculosis and other lung infections by inhibiting efflux pump and biofilm formation and acting as a potential anti-bacterial agent (Sharma et al., 2019; Danquah et al., 2021)

Unani medicinal system is considered as one of the oldest traditional medicines (Khan et al., 2020). Manuscripts such as *Kitaab-al-U'mdah fil-Jeraahat* (Part II), *Kaamil-al-Senaa'h* (Part I), *Al-Qaanoon fil-Tibb* (Vol. V) have mentioned formulations containing onion as a major ingredient (https://www.tkdl.res.in/). *Tila-e-seer* is a formulation for the treatment of alopecia or alopecia furfuracea (scalp and hair fall). The claims have been validated by clinical studies where application of onion juice has improved hair growth and was effective in reduction of alopecia areata (Sharquie & Al-Obaidi, 2002). Another Unani formulation *Sikanjbeen -e-Unsuli* helps in treatment of hepatalgia, spleenalgia, ascites, bronchial asthma (Akhtar et al., 2011). One of the most popular Unani formulations over several centuries with mention in several Unani pharmacopeia is *Majoon-e-Piyaz. Majoon-e-Piyaz* is a dark brown coloured semi solid preparation prescribed for premature ejaculation. Unani pharmacopeia recommends the *Majoon-e-Piyaz* formulation as aphrodisiac, semen retentive and for treatment of sexual debility and spermatorrhoea (https://pcimh.gov.in/show_content.php?lang=1&level=1&ls_id=58&lid=56). *Majoon-e-Piyaz* formulation contains onion juice as the major ingredient followed by sugar and mixture of herbs including dried onion seeds (Shah et al., 2011).

The aphrodisiac and testosterone enhancing properties of onion and its extracts were reviewed by Banihani (2019). The aqueous onion extracts at concentrations of 30 mg day^{-1} improved the testosterone levels in males by enhancing the production of lutenizing hormone, scavenging of free radicals and improving the antioxidant status in testis (Khaki et al., 2017). Further the onion extracts were found to stimulate nitric oxide synthesis in Leydig cells (Grman et al., 2011). The quercetin enriched onion extracts were found to maintain the energy homeostasis in Leydig cells and enhance testosterone production by modulating the activity of 5′ AMP-activated protein kinase enzyme which enhanced the fatty acid oxidation and glucose uptake in the cells (Rivera et al., 2016; Kim & Min, 2018).

3. Onion production in India

Onions (*Allium cepa* L.) are a significant vegetable crop in India, both for domestic consumption and export. The three major varieties grown in India are yellow, white, and red onions, which cover a large portion of the cultivation area. Unlike in other countries where onions are grown in temperate conditions, India's cultivation areas mostly fall under tropical conditions (Lawande et al., 2009). India's top onion producing state is Maharashtra contributing to 42.53% of country's onion production (MAFW, 2020). The other major states producing onions in significant quantities are Gujarat, Madhya Pradesh, Karnataka, Rajasthan, Bihar and Haryana.

Onions are seasonal crop with sowing and harvesting periods distributed throughout the year spreading across different geographical regions. The sowing and harvesting periods vary between the different states. Generally, in India onions are cultivated during three seasons *viz*., autumn (kharif), late autumn (late kharif) and winter (rabi) contributing to approximately 20%, 20% and 60% of India's total onion production respectively (Thangasamy et al., 2023). The harvesting periods for these seasons are March to June for winter crop, October to December for autumn crop and January to March for late autumn crops (MAFW, 2020). For the year 2019-2020, the total onion production during autumn, late autumn and winter was 3.90, 1.57 and 21.241 million tonnes respectively. Nearly 60-65% of the total onion production during autumn season is primarily used for domestic and storage purpose and meet the consumer demand till the arrival of winter onion in the market (Sharma et al., 2017). Onions are a cool season crop primarily cultivated in winters, however, considering the huge domestic demand for onions and the price volatility, several varieties have been developed adapting to tropical conditions, especially the autumn and late autumn varieties to meet the supply demand and for price stabilization (Thangasamy et al., 2023).

3.1. Onion varieties in India

In India nearly 35 different varieties of onions are produced and utilized for variety of applications (supplementary table S1). The varieties are categorized based on their colour, no. of days required for maturity, total soluble solids (TSS), and yield. The major factor that determines onion market is the bulb colour. Uniform bulb pigmentation is preferred trait in the market and consumer preference studies has indicated that red coloured onions are most sought after (Khandagale & Gawande, 2019). Onions have wide range of colour shades *viz*., red, white, yellow, golden, pink, and chartreuse. These wide variations in coloration of the bulbs could be attributed to the presence of anthocyanins (Khandagale & Gawande, 2019). As mentioned earlier, the major-coloured varieties of onions produced in India are red, white and yellow respectively. The average no. of days required for maturity of onion bulbs range between 110-120 days with few varieties requiring shorter duration such as CO-1, CO-2, MDU-1 and Agrifound Red with less than 80 days for maturity (refer supplementary table S1). On the contrary certain varieties such as Agrifound light red, Spanish Brown, Agrifound white require between 145-160 days to maturity, sometimes close to 180 days (refer supplementary table S1). Another important parameter used for the classification of onion varieties is the storability of the bulbs. Storability can be classified into three categories, viz., poor (1 to 1.5 months), medium (2-3 months) and good (5-6 months). The onion varieties that grow during winter season have longer storability compared to late autumn or autumn crops (Ghosh et al., 2022). The storability of onion bulbs is affected by both pre-harvest and post-harvest conditions. Among the preharvest conditions, the cultivar genotype, irrigation, use of fertilizers and harvest stage affect the storability of onions. Likewise, curing conditions, particularly temperature and leaf retention affect the storability of onions (Petropoulos et al., 2017). Another factor that is crucial is the total soluble solids (TSS) content of onion. Indian onion varieties are mostly short-day crops and do not possess TSS higher than 15°Brix (Lawande et al., 2009). The average range of TSS, generally measured as °Brix, ranges between 11 to 14°Brix, with some varieties possessing higher TSS content such as Agrifound red, Agrifound rose (15 – 16°Brix) and in some cases up to 18°- 20°Brix such as Arka ujwal and Arka swadista (supplementary table S1). There are several factors affecting the TSS content of the onion bulb, namely genotype of the variety, irrigation, nitrogen fertilization and storage humidity conditions (Lawande et al., 2009). Dry matter (DM) and TSS are major factors that are used for determining the storability and dehydration yield of a variety. It has been observed that white onion varieties generally contain low TSS ranging from 10-14% and are not suitable for dehydration process whereas red genotypes possessing higher TSS are usually preferred for dehydration and other value addition applications (Islam et al., 2019).

4. Harvesting of onion

Onion harvesting is a combined operation consisting four critical steps, *viz*., (de)topping, lifting, curing and transporting from field to warehouse. Harvesting of onion decides the quality and storage life of the bulbs. In general, onions are harvested after 70-90 days after transplantation process and in some varieties up to 110-120 days. The harvesting time is indicated when the onion leaf turns yellow from green on the top and simultaneously collapse just above the top of the bulb. In the case of large-scale harvesting, harvesting is done after half of the tops are fallen down but when the leaves are still green (Kumawat & Raheman, 2022a). In some cases, like with onions produced during autumn, the tops do not fall off, but the bulbs are harvested when the leaves turn yellow. For winter cultivars, harvesting is done typically about one week later, when 50% of the tops have fallen. Improper harvesting such as early harvesting results in sprouting while delayed harvesting of bulbs results in higher root growth during storage (Kumawat & Raheman, 2022b). Further, irrigation plays an important role in the quality and storability of onion bulbs post-harvest. Onion is a shallow rooted crop and requires frequent but light irrigation to maintain optimum soil moisture and bulb development. Irrigation is generally stopped when the bulbs mature, *i.e.*, 2 weeks (12-15 days) before the harvest. Excessive irrigation (twice or more per week) before harvest may increase the bulb size but reduce the storability of bulbs owing to increase in the moisture content of the bulbs leading to microbial contamination and other post-harvest losses such as sprouting (Brewster, 2008).

4.1. Topping

As described earlier, the major steps involved in harvesting of onions are detopping, lifting and curing (Wright & Triggs, 2005). The process of lifting and topping are interchangeable. Traditionally onions are harvested manually by loosening the soil using forked tools and pulling up the onions from ground, usually called lifting, followed by de-topping (removal of leaves). This process is both labour and time intensive and generally women folk are involved in India. The process involves use of sickle to detop the dried leaves and it was estimated that approximately 12.5-woman hours is required for detopping 1 tonne material (onion bulbs) (Rathinakumari, 2022). Alternatively, in recent years detopping (field toppers) and crop lifting machines are being utilized for removal of the dried leaves and lifting of the bulbs from the soil. Several machine designs have been proposed and utilized for achieving lifting and detopping.

Kumawat & Raheman (2022a, b) developed a machine for topping of the leaves. The design consisted a rotary cutting unit in a processing trolley, a guide rail and onion plant holding units. The cutting unit consisted a pair of nylon rope attached to a rotary drum. The leaf topping unit could be attached to a tractor or power tiller operated onion harvester. The processing unit had provision to vary the speed of the cutting unit as well as forward speed. The authors observed that the cutting speed should be below 1800 RPM and the forward speed of the processing trolley should be less than 1.2 km h^{-1} to achieve good topping efficiency. The mean power required for topping of onion leaves was in the range between 250 – 300 W.

Rathinakumri & Kumaran (2022) designed a roller based detopping machine consisting a set of detopping rollers with cutting edges, a frame and power transmission system. The onion bulb tops are drawn between the rollers due to the counter rotating action of plain and cutting rollers and have an orientation of tops down position. The sharp edges of the cutting rollers detops the onion. The plurality of the rollers ensures higher chances for detopping and conveys the detopped bulbs for further delivery. The detopping efficiency of the equipment was 95.2% with a very low percentage of damages to the bulb (2.3%). The percentage of non-detopped bulbs were only 2.50%. The equipment had a capacity to detop nearly 372 kg h^{-1}. The equipment reduced the drudgery and operating cost reduction by 37%, primarily labour charges, when compared to the conventional manual process. The various designs developed for lifting and detopping of onion bulbs are presented in Fig. 3. Topping is a crucial step in harvesting of onion. Cutting of foliage resulting in a short neck (< 5cm) leads to exposure of the bulb layers causing rotting while bulbs with longer necks (7.5 cm to 12.5 cm) show lesser risk of rotting. Early topping increased the chance of bulb rotting by 69.2% during harvesting and storage period (Belo et al., 2023).

4.2. Lifting

As described earlier, lifting is another crucial step that influences the storability of the onion bulbs. Lifting involves digging of the bulbs from soil. Lifting is done commonly when the foliage has collapsed or 60–80% of the tops down. Sometimes they are lifted earlier at 10–50% tops-down or late >90% tops-down (Wright & Triggs, 2005). It has been observed that late lifting results in enhancement of the nutritional quality of onion, indicated by increase in concentration of quercetin and its derivatives by 45% when compared to early lifting (Ren & Zhou, 2021). The correct time of lifting speeds up the curing process, by preventing the bulbs from excess moisture uptake from the soil and fastening the drying of the top and neck. Lifting of immature bulbs, i.e., lifting too early when only 25% of the leaves have fallen, results in excess moisture and delays the curing time increasing the chances for microbial diseases such as neck rot (Wright & Triggs, 2005).

Naik et al. (2022) developed a machine "onion digger with cutter bar topping unit" performing both lifting and topping operations for efficient harvesting of onion bulbs (Fig. 3). The equipment demonstrated a maximum digging efficiency of 93.76% with a damage percentage of 6.44% and topping efficiency of 78.46%. Soil moisture content, rake angle and travel speed where the important parameters that affected the efficiency of the process. Lower rake angle (14°-16°) and lower moisture content (11.2% - 12.8%) yielded better digging efficiency with higher soil separation as only a minimum volume of soil is dug. The optimum values field efficiency of the equipment was 85% and the total area that could be covered was 0.17 ha/h.

In large scale operation, foliage and unwanted weeds are removed by field toppers followed by windrowing where the onion bulbs are lifted from their beds. Windrowing is done generally 1 -2 weeks before sending the onions for further storage. After windrowing onion bulbs are cured by field drying. Some researchers have observed that bulbs harvested when the 75% of top fall followed by curing for 1 to 2 weeks showed better visual and keeping quality (Muhie, 2022)

4.3. Curing

Curing is a drying process carried out to remove the excess moisture from the outer skins, roots and neck tissues of harvested onion bulbs. Onion is generally harvested when 50-80% of the top fall and leaves are dried and withered. Curing enhances the keeping quality of the onion bulbs and reduces the chances of infection by microorganisms during storage (Petropoulous et al., 2017). During curing, moisture is removed only from the outer scales, rather from throughout the bulb resulting in dried surface skin. The dried outer or surface skin provides mechanical barrier against water loss, defence against microbial attack and gives cosmetic appearance to onion (Gorreapti et al., 2017). Onions are considered cured when their neck is tight and the outer scales are dried when they have 3 to 5% of their weight (Rani, 2016).

Curing is performed either by natural or artificial methods. In traditional and small-scale operations, curing is performed by windrowing method. This method involves harvesting of mature bulbs and laying them on their sides on the soil surface to dry for 10 -15 days in hot tropical climate. During the curing process, onion bulbs are covered by dried onion leaves for preventing sun-burn (Opara, 2003). Freshly harvested bulbs are cured in ambient conditions in the field for 2-3 days followed by removal of foliage leaving 2-3 cm of the neck followed by shade curing for 10-15 days (Abbas & Ali, 2013; Gorreapti et al., 2017).

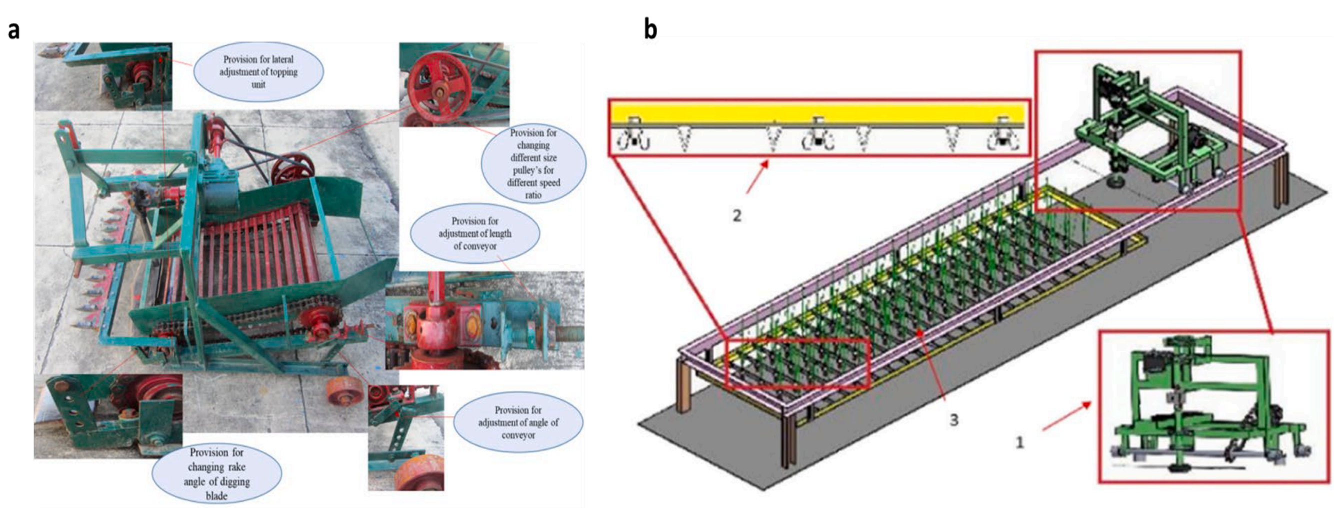


Fig. 3. Various machines involved in onion harvesting (a) adapted from Naik et al. (2022); b) adapted from Kumawat and Raheman (2022a) where 1, 2 and 3 refers to Processing trolley, Plant holding units and Onion plants respectively.

Natural curing of onion bulbs by windrowing method is largely practiced by Indian farmers.

However, the major challenge with filed curing is the dependence on climatic conditions. Unexpected rainfall and moist conditions extend curing time often leading to spoilage of bulbs during storage. It has been estimated that almost 30-40% of onion bulbs produced in India undergo spoilage due to improper curing and storage (www.icar.org.in). This necessitates curing by artificial means. The grand onion challenge posed by Government of India for enhancing shelf life and storability of onions recommends development of forced or artificial curing methods (https://doca.gov.in/goc/assets/document/Grandchallenge-Document.pdf).

5. Major problems associated with onion cultivation and storage

Onions, while having a relatively longer shelf life compared to other vegetables, are still susceptible to spoilage if not stored properly. Onion spoilage is a global issue with nearly 8300 thousand metric tonnes lost due to process wastage and spoilage. As per the estimate by FAO and APEDA (FAOSTAT, 2021; APEDA, 2021) out of 22 million metric tonnes produced in India, nearly 1.68 million tonnes are lost due to microbial spoilage (Savitha et al., 2022). Factors responsible for onion spoilage are rotting and spoilage causing 15-20% of the loss, sprouting affecting 8-10% of the crops, and physiological weight loss contributing up to 30% (Tripathi & Lawande, 2015). According to APEDA (2021) and Kiran et al. (2024), approximately 35-40% of the onion crop produced in India is lost due to abovementioned factors and ineffective post-harvest management practices. Onions are living tissues that can undergo chemical changes even after harvest, and their storability is influenced by factors such as temperature, humidity, and atmospheric conditions during storage. Storability refers to the onion's ability to maintain its quality and quantity while being stored close to the consumer without any deformities (Sharma & Lee, 2016).

The overall quality of post-harvest onion bulbs is dependent on their physical properties, which are influenced by factors such as the cultivar type, irrigation methods, maturity, harvest time, and the pre- and post-harvest treatments applied to the onions (Muhie, 2022). The following sections will describe the various factors that contribute to the deterioration of onions.

5.1. Rotting

Rotting is the process of decay in onions, leading to an unpleasant appearance and odour. Bacterial and fungal contaminations are the primary reasons behind onion rot. Factors that promote microbial contamination include over-irrigation or rainfall after the maturity stage of onions. The rotting process increases the rate of respiration, causing an excessive release of carbon dioxide, resulting in the generation of heat, loss of moisture, and reduced shelf life of onion bulbs (Abbas & Ali, 2013). While various microorganisms can cause onion rot, fungi are the main agents responsible for pre- and post-harvest losses in onions. Approximately 35-40% of onion losses are due to damage caused by storage diseases, with fungal bulb rot accounting for about 15-30% of losses in different varieties (Kleman, 2023). Fungi and bacteria are possible causes of pre- and post-harvest losses in onions. High storage temperature (28-34°C) and humidity (> 75% RH) are factors that promote microbial contamination as these warm and moist conditions promote fungal growth (Steentjes et al., 2021). Another important factor that increases the chance of microbial infestation are excess irrigation before harvesting resulting in the formation of succulent bulbs with high moisture content that are susceptible to rotting (Muhie, 2022). Biswas et al. (2010) observed that irrigation at 10-day and 15-day intervals resulted in higher yields but significant losses during storage due to rotting. Further the authors observed that with a higher frequency of irrigation during the growing period there were no significant improvement in the bulb yield, rather there was an increase in the rotting percentage. In addition to these, injury of bulbs during harvesting is another crucial factor that promotes rotting. The most commonly occurring microbial diseases that affect onion bulbs in India are listed below

5.1.1. Black mold

The fungus causing black mold is mainly *Aspergillus niger*, which resides in soil, forage, organic debris, and food products, causing disease during the postharvest stage of onion bulbs. The disease is commonly seen in onions stored in hot climates, with temperatures ranging between 30°C to 45°C. The infection is recognized by the presence of black powdery spores on the outer scales. Visible black mycelia and conidia are observed between the neck region and the outermost scales of the onion. It can also grow inside the bulb as dark discoloration spreading from the neck area (Kumar et al., 2015).

5.1.2. Fusarium basal plate rot

Fusarium basal plate rot is another type of highly impactful disease in onions, caused by *Fusarium oxysporum* f. sp. *cepae*. It can occur at any point during the growing season and can cause plants to bend and eventually die, or lead to slow rotting of bulbs starting from the basal plate. This pathogen is commonly found in the soil and has a strong ability to invade the bulb independently. Infection may be facilitated by previous damage during harvesting and transportation (Kleman, 2023).

5.1.3. Neck rot

Neck rot is a post-harvest disease of onions caused by fungi such as *Botrytis aclada, Botrytis allii*, and *Botrytis byssoidea* (Steentjes et al., 2021). This disease, first described in 1925, primarily affects the bulb tissue during storage. Symptoms, such as decay starting at the neck and spreading throughout the bulb, are often not visible in the field, making it challenging to predict the occurrence of neck rot during storage. The affected scales in the neck area become translucent, decay, and show greyish-colored mycelium growth between them (Steentjes et al., 2021).

5.1.4. Blue mold

Penicillium spp. cause storage diseases known as blue mold or green mold in onions. Symptoms include yellowish, reddish, or watery stains and lesions, leading to bulb shattering. These pathogens thrive at temperatures of 15-32°C in moist conditions (Kleman, 2023). *Penicillium* spp. are usually found in the soil and often invade plants through previously damaged tissue, and infect healthy bulbs also.

5.1.5. Downy mildew

Peronospora destructor causes Downy mildew, which is considered one of the most severe onion diseases as it affects the soil and leads to significant yield loss. The disease primarily affects onion leaves during the growing season, causing them to bend, twist, and turn yellow before drying out (Kim et al., 2020). Symptoms include a violet growth of fungus on the leaf surface and flower stalk, which later appears pale greenish-yellow, leading to damage of the leaves or seed stalks. If symptoms are not detected before harvest, the infection can spread to the onion bulbs, causing them to wilt or sprout prematurely during storage. The latent period of downy mildew disease is approximately 9–16 days.

5.1.6. White rot

Sclerotinia cepivorum causes white rot, a widespread and destructive fungal disease of onions. The disease primarily affects the leaves but can also infect the bulbs. Seeding death is rapid but rare. Symptoms on leaves are observed only when the pathogen starts growing into the bulb. Common symptoms include premature yellowing, which turns purplish, then dark brown or black, and the dying of older leaves, stunting of plants, and eventual death of foliage (Schwartz & Mohan, 2007). Infected onion bulbs become soft and appear translucent, with a white, fleecy growth of mycelium and abundant black sclerotia resembling mustard grains. The disease thrives at temperatures ranging from 21-30°C with 80-90% relative humidity (Tripathi & Lawande, 2019).

5.1.7. Purple blotch

Purple blotch, caused by *Alternaria porrii*, has been reported on *Allium* spp. and may occur on other species as well. The fungus can infect bulbs during harvest, entering through the neck or wounds on the onion. Symptoms first appear as small (2-3 mm), translucent lesions on leaves or seed stalks, which quickly develop white centers (Schwartz &-Mohan, 2007). As the lesions enlarge, they form a brown to purple zone, with the surface covered in brown to dark grey fungal spores in moist conditions. Larger lesions on leaves can girdle the leaf, and lesions may also affect seed stalks and flower parts, preventing seed development.

5.1.8. Slippery skin and sour skin

Slippery skin and sour skin are types of bacterial rot in onions caused by *Erwinia* spp., *Burkholderia gladioli* subsp. *Alliicola* and *B. cepacia*. Slippery skin symptoms include the softening of individual scales inside infected bulbs, which escape when squeezed. Sour skin has similar symptoms to slippery skin, with initial infection in the field leading to yield losses of 5-50%, often continuing in stored onions (Schwartz & Mohan, 2007). The disease causes rotting of individual scales inside the bulb, leaving outer scales soft but the bulb appearing healthy (Kleman, 2023). Symptoms of soft rot include slimy, pale yellow to light brown decay starting on inner layers of the bulb. Initially, affected bulbs may appear healthy externally, with softening of the neck region tissues. When cut vertically, water-soaked, soft inner layers with an acetic acid odour and creamy yellow or yellow-brown discoloration are visible. Later, infected tissues dry out, causing bulbs to shrink.

5.1.9. Mushy rot

Various bacterial groups can cause similar symptoms of rot in onion bulbs. Infections by *Erwinia* spp., known as mushy rots, can occur wherever onions are grown, although they are infrequent. Soft mushy spots appear, especially around the bulb neck region, spreading down and throughout the onion bulb, similar to neck rot caused by fungi. The decaying tissue may show the growth of white mold with minor black specks. Mushy rot is firmer than sour skin and slippery skin, and the rot develops in a ring-like pattern (Kleman, 2023).

5.2. Weight loss

Onion bulbs contain approximately 85-90% water and physiological weight loss in onions refers to the natural loss of weight and moisture content after harvesting of bulbs. Onion bulbs loose water mainly due to respiration and transpiration. Storage conditions such as temperature, humidity, air movement and atmospheric pressure influence the rate of water loss (Abu-Goukh et al., 2001; Tripathi & Lawande, 2019). It has been observed that storage of onions under ambient conditions cause 5-6% weight loss per month of storage. In an experimental study, Tripathi and Lawande (2006) reported a 23% weight loss in bulbs stored under ambient conditions for 4 months compared to the ones stored under low temperature (0-2°C). Higher storage temperatures (>25°C) increase respiration rate which in turn results in weight loss (Biswas et al., 2010). In addition to these, injury during harvesting and premature harvesting results in weight loss. This is because immature onions have fewer outer scales and higher moisture content and are prone for microbial contamination and weight loss (Muhie, 2022).

5.3. Sprouting and Rooting

Sprouting and rooting are the two important factors that causes maximum deterioration of bulbs during long term storage of onions. A typical life cycle of onion consists of three stages, *viz*., rest, dormant and regrowth (Sharma et al., 2016). During the rest period (4-6 weeks), the mature onion bulbs are resistant to rapid environmental changes and there is a negligible cellular activity. The activity of growth promoting factors such as endogenous hormones (cytokines, gibberelins and auxins) are very low while the activity of growth inhibitors such as abscisic acid and ethylene are high (Sharma et al., 2016). Immediately after harvesting, onions are under natural state of dormancy. However, during dormant stage the bulbs respond to environmental variations. In the initial stages of dormancy, the impact of environmental conditions on onion bulbs is slow; and as the time progresses the changes are rapid (Yasin & Bufler, 2007; Muhie, 2022). Dormancy is a physiological state where the activity of several key metabolic enzymes such as invertase, phenyl-alanine ammonia lyase, peroxidase is very low (Benkeblia et al., 2000). In this period, a slow rate of source to sink transition occurs keeping the bulb metabolically active although at a very low rate. Scales contain carbohydrates and act as source while base plate where sprouting occurs acts as sink. During dormant stage, the activity of enzyme invertase is very low preventing carbohydrate mobilization (Sharma et al., 2016).

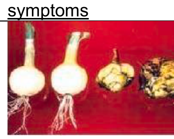
The regrowth phase or sprouting that follows the dormant period is when several physiological changes occur such as high source to sink transition involving remobilization of carbohydrates from scales to basal plate, increase in the rate of respiration, enhanced activity of growth promoting hormones (Pak et al., 1995; Chope et al., 2012). Additionally, changes in biochemical composition such as phenolics, flavour compounds and disaccharide to monosaccharide ratio in bulbs are few indicators of sprouting (Petropoulos et al., 2017). Bulbs undergo growth activities including visible growth of stem through neck. The reallocation of water and metabolites from scales to a base plate is the first step in sprouting (Yasin & Bufler, 2007). Apart from the tight regulation of growth hormones and source to sink mobilization, the dormancy and sprouting in onion bulbs are maintained and regulated by specific gamma-glutamyl class of peptides such as gamma-glutamyl propenyl cysteine sulphoxide and 2-carboxypropyl glutathione (Lancaster & Shaw, 1991). These are defensive compounds accumulated during dormancy. During sprouting these compounds are hydrolyzed and they prevent the sprouting bulbs from pathogen attack. Concentration of these compounds could be used as an indicator for determination of sprouting (Petropoulos et al., 2017). Factors affecting sprouting and rooting are genetic makeup of the onion variety, bulb moisture content and external environmental conditions such as temperature, and humidity. The triggering factors are higher atmospheric oxygen concentration, higher temperature (>27°C) and high relative humidity (>70% RH) that increases rate of respiration that induce sprouting and rooting in onion bulbs (Brewster, 2008). It has been observed that at higher storage temperature the activity of growth promotors is increased leading to sprouting. Further, injury to bulbs induce sprouting and concomitant weight loss (Petropoulos et al., 2017). Rooting also results in microbial contamination leading to onion root rot disease. Long term storage of bulbs under low temperature (< 5°C) and high relative humidity >80% RH results in root rot. The details of various diseases affecting onion bulbs are tabulated in Table 1.

6. Pre-and post-harvest techniques in disease management of Onions

6.1. Pre-harvest techniques

To meet year-round market demand, a significant amount of onion bulbs is stored under controlled conditions to maintain quality and prevent rotting. The goal of storage is not just convenience but also to preserve quality and minimize losses. Due to the perishable nature of onions, proper processing and storage are essential. The onion's journey from farm to consumer involves pre-harvest, harvest, and post-harvest stages, each requiring specific techniques to maintain quality. Pre-harvest conditions are influenced by factors such as soil quality, genetics, growing conditions, and cultivation practices like irrigation and

Table 1
List of various onion diseases prevalent in India (Mishra et al., 2014; Kumar et al., 2015; Kleman, 2023; AboelAinin et al., 2024; Kiran et al., 2024; Srinivasan and Shanmugam, 2006; Abd-Alla et al., 2006; El-Dawy et al., 2024; Vijayrao, 2024; Steentjes et al., 2021; Raju and Naik, 2006; Tripathi and Lawande, 2019; Develash and Sugha, 1997; Schwartz and Mohan, 2007; Abdalla et al., 2013).

Diseases	Causing Agent	Images	Prevalence in India	Disease exacerbating environmental conditions	Control methods	Reference
			Fungal Diseases			
Black mold	*Aspergillus niger*	 Source: https://vikaspedia.in/agriculture/crop-production/integrated-pest-managment/ipm-for-vegetables/ipm-strategies-for-onion/diseases-and-symptoms	Contributes to 80% of onion rotting	Temperatures: >30 °C Relative Humidity: 90–100%	• Acetic acid (0.2 g L $^{-1}$) and H_2O_2 (4.0 g L $^{-1}$) • Methyl benzimidazol-2-ylcarbamate (Carbendazim) 0.1%, Copper oxychloride 0.25%, Ethylenebis dithiocarbamate (Mancozeb) 0.25% • Acetic acid 0.3% and 0.4% concentrations also inhibit mycelial growth • Sulphur gas fumigation	Kumar et al., 2015; Kleman, 2023 AboelAinin et al., 2024 Kiran et al., 2024 Srinivasan & Shanmugam 2006 Abd-Alla et al., 2006 El-Dawy et al., 2024
Fusarium basal plate rot	*Fusarium oxysporum* f. sp. *cepae*	 Source: https://vikaspedia.in/agriculture/crop-production/integrated-pest-managment/ipm-for-vegetables/ipm-strategies-for-onion/diseases-and-symptoms	17.29 to 30.55% of microbial infestation	Temperature: optimum at 28 to 32°C	• Seed treatment with Thiram (2g/kg of seed) • Usage of carbendazim (Methyl benzimidazol-2-ylcarbamate), Thiophanate Methyl (Topsin-M) or Benomyl 0.1% • Cold plasma treatment	Kleman, 2023 **https://nhb.gov.in/pdf/vegetable/onion/oni002.pdf** Vijayrao, 2024 Mishra et al., 2014
Neck rot	*Botrytis allii* and *Botrytis aclada*	 Source: https://agritech.tnau.ac.in/crop_protection/crop_prot_crop%20diseases_veg_onion.html	62.6% of microbial infestation	• Excessive nitrogen (> 200 kg ha^{-1} doses • Excessive irrigation	• Benzoyl and carbendazim (Methyl benzimidazol-2-ylcarbamate) @ 0.5% • Effective curing	Steentjes et al., 2021 Kiran et al., 2024 **https://nhb.gov.in/pdf/vegetable/onion/oni002.pdf**
Blue mold	*Penicillium* spp.	 Source: https://vikaspedia.in/agriculture/crop-production/integrated-pest-managment/ipm-for-vegetables/ipm-strategies-for-onion/diseases-and-symptoms	na	Temperatures between 15-32 ˚C	• Carbendazim (Methyl benzimidazol-2-ylcarbamate) 0.1% • Benomyl • Cold plasma treatment	Kleman, 2023 Raju & Naik, 2006

(continued on next page)

Table 1 (*continued*)

Downy mildew	*(Peronospora destructor)*	 Source: https://vikaspedia.in/agriculture/crop-production/integrated-pest-managment/ipm-for-vegetables/ipm-strategies-for-onion/diseases-and-symptoms	na	Warm and humid climate	Metalaxyl (methyl N-(methoxyacetyl)-N-(2,6-xylyl)-DL-alaninate) + mancozeb (ethylenebis dithiocarbamate)	Kleman, 2023 Tripathi, & Lawande, 2019 Develash, & Sugha, 1997
White rot (Sclerotinia rot)	*Sclerotinia cepivorum*	 Source: https://agritech.tnau.ac.in/crop_protection/crop_prot_crop%20diseases_veg_onion.html	na	na	Seed treatment using Thiram (4 g/kg of seed) and drenching of soil with 0.25% Mancozeb (Ethylene bisdithiocarbamate)	Schwartz & Mohan, 2007 **https://nhb.gov.in/pdf/vegetable/onion/oni002.pdf** Tripathi, & Lawande, 2019
Purple blotch	*Alternaria porrii*	 Source: https://agritech.tnau.ac.in/crop_protection/crop_prot_crop%20diseases_veg_onion.html	na	Dew or rain plays role for sporulation or infection. Hot and humid climate ranging from 21-30°C and RH 80-90% favour the development of the disease. Common during autumn season	Usage Fungicides, 0.25% Mancozeb (Ethylene bisdithiocarbamate) 0.1% Tricyclazole, 0.1% Hexaconazole, 0.1% Propiconazole	Kleman, 2023 **https://dogr.icar.gov.in/index.php?option=com_content&view=article&id=121&Itemid=192&lang=en** **https://nhb.gov.in/pdf/vegetable/onion/oni002.pdf** Tripathi, & Lawande, 2019
			Bacterial diseases			
Bacterial soft rots	*Erwinia carotovora* ssp.	 Source: https://vikaspedia.in/agriculture/crop-production/integrated-pest-managment/ipm-for-vegetables/ipm-strategies-for-onion/diseases-and-symptoms	na	Higher storage temperatures (>30°C)	Propionic acid spray	Kleman, 2023 Abdalla et al., 2013
Slippery skin	*Burkholderia gladioli* subsp. *Alliicola*	 Source: https://www.plantdiseases.org/slippery-skin-onion	6% of microbial rotting		na	Kleman, 2023 Kiran et al., 2024
Sour skin	*Burkholderia*, *B. cepacia*	 Source: https://www.ipmimages.org/browse/subinfo.cfm?sub=16560&area=86	4.5% of microbial rotting	Excess water and nitrogen before harvest Over maturity and wounding Storage temperatures 30°C under moist conditions	na	Kleman, 2023 Kiran et al., 2024

Na= data not available

chemical use. Practices like timely transplantation and harvesting can reduce sprouting during long-term storage of onion bulbs (Petropoulos et al., 2017).

6.2. Irrigation

Irrigation plays an important role in plant growth and onions are considered as moderate water consumers. Irrigation requirements for onions depend upon the season, soil type and method of irrigation. In a typical life cycle, irrigation is done at the time of transplanting, three days after transplantation and subsequently in a 7–10-day interval depending on the soil moisture and climatic factors The total number of irrigations depend on the season. During autumn (Kharif season), onions need 5-8 irrigations. During late autumn (late Kharif) and winter (Rabi) season, the irrigation requirements increase by 10-15 irrigations (https://dogr.icar.gov.in/). Irrigation is generally stopped when the crop attains maturity (typically 12-15 days before harvest) and when the tops fall. Irrigation is one of the important factors that determines the storability of onion bulbs. The ideal water requirement is the irrigation to a depth of 2.5 cm once a week. Excessive irrigation (twice or more per week) leads to increase in the moisture content in bulbs consequently leading to sprouting and rotting (Muhie, 2022). Further increasing the irrigation frequency reduced dry matter content of bulbs (Ortola & Knox, 2015).

In addition to number of irrigations, the method of irrigation significantly affects the quality of onion bulb. Onion being a shallow rooted crop need only a light irrigation for maintaining optimum soil moisture supporting growth and bulb formation. Both excess irrigation and dry spell affect the bulb quality. Flood irrigation has been reported to be ineffective with seepage and percolation losses. Improper irrigation practices cause water logging leading to spoilage of bulbs (Tripathi & Lawande, 2016; https://dogr.icar.gov.in/). Excessive water logging results in non-availability of oxygen to plant which can even cause death of plant (Bhasker et al., 2018). Modern irrigation techniques such as drip and micro sprinkler irrigation have been reported to increase bulb yield and reduce water loss. According to Tripathi & Lawande (2019) storage losses in drip irrigation were approximately 13.4% while in surface irrigation it was nearly 18%. Apart from excessive irrigation, water deficit conditions also affect bulb yield. Onions are more susceptible to water stress (drought) during the bulb formation stage compared to vegetative growth phase. Water stress (drought) results in a shortened period of bulb growth, resulting in the production of smaller bulbs with low dry weight (Kiran et al., 2024). Under Indian conditions, utilizing cut-off irrigation techniques have been suggested to be beneficial for enhancing the onion yield, bulb quality, and better storability.

6.3. Soil Nutrients

Manures and fertilizers are essential for maintaining soil fertility and improving the quality of onions. The choice of chemical fertilizers, such as nitrogen, potassium, and sulphur, plays a crucial role in determining onion yield, size, and quality. Excessive use of chemical fertilizers can result in higher rates of sprouting during storage compared to a combination of chemical and farm manure (Tekeste et al., 2017). Excessive use of nitrogen fertilizer can result in larger onion sizes with broader neck (also called as bull neck) increasing the susceptibility to bacterial diseases. High nitrogen levels in the soil can cause moisture retention in onion bulbs during field curing, making them more prone to rot due to microbial colonization (Belo et al., 2023). Another important nutrient that determines the physicochemical properties of onion bulbs is sulphur. It has been observed that application of sulphur at 45-50 kg ha^{-1} enhances the concentration of precursor molecule, S-alk(en)yl-L-cysteine sulfoxide that contributes the unique flavour and pungent aroma of onion bulbs (Petropoulos et al., 2017). The use of manure in comparison with chemical fertilizer has been found to improve the storage life, however significant losses have been reported (Tripathi and Lawande, 2019). Chemical fertilizers, being rich in nitrogen, can increase weight loss (3.39-21.47%) by promoting soft tissue formation with high moisture content, making bulbs more susceptible to bacterial and fungal attacks consequently leading to rotting. Integrated application of organic and inorganic fertilizers improves the productivity, storability of onion bulbs with minimal rotting and sprouting. In a study by Tekeste et al. (2017), For example, integrated application of 69 Kg N ha^{-1}, 92 Kg phosphorus ha^{-1} and 20 Mg manure ha $^{-1}$ can be a good compromise for postharvest quality and shelf life of onion bulbs. Further, optimum dry matter content (DM), pungency and total soluble solid content (TSS) of bulbs were observed with application of potassium (K_2O) between 75 and 100 kg ha^{-1} (Sankar et al., 2009; Tekeste et al., 2017). Application of potassium at various growth stages resulted in significant reduction in the percentage of rotting and sprouting in onion bulbs (Masalkar et al., 2005; Kumara et al., 2018). In another study, application of 120 kg N ha^{-1}, 90 kg P ha^{-1}, 90 kg K ha^{-1}, 45 kg S ha^{-1}, 5 kg Zn ha^{-1} and 5 Mg cow dung ha^{-1} have been found to improve the total dry matter content of the bulb and other yield parameters (Tripathy et al., 2016; Bayoumi et al., 2019). Excess sulphur (> 60 kg ha-1) resulted in decreased neck thickness and reduced the storability of bulbs (Kumar et al., 2002).

6.4. Chemical Treatments

As discussed in previous sections, sprouting and rooting during storage of onion bulbs are undesirable characteristics. These can be controlled by use of chemical agents such as growth inhibitors, specifically sprout suppressants such as maleic hydrazide (MH) (1,2-dihydro-3,6-pyridazinedione) and growth modulators such as chlormequat (2-chlorethyl) trimethyl ammonium chloride, a tertiary ammonium salt, commercially sold under the brand name Wylom OP. They function by reducing the rate of respiration during storage. For example, MH treated onion bulbs shows 1-2% sprout after 2-3 weeks storage of onion bulb at 24°C (Adamicki, 2004). The MH acts as an antagonist by entering in to the cell and replacing the cytosine, a building block of RNA, ultimately obstructing the protein biosynthesis and cell development (Muhie, 2022). Usage of chemical sprays before harvesting helps in minimizing the physiological changes and quality attributes such as TSS, pyruvic acid content, ascorbic acid content, soluble protein, and sulphur content in the bulbs. The TSS content of onion bulbs after treatment with Wylom OP at 1000 mg kg^{-1} ranged between 22 and 24°Bx, much higher in comparison to control (untreated plants) which had 18-20°Bx TSS after 90 days of storage (Vethamoni, & Gomathi, 2018). Treatment with Wylom OP increased the bulb weight and reduced the loss of moisture during storage. The average moisture content in Wylom OP treated bulbs were approximately 85.7% while that of control (untreated) bulbs were 79.8% (Rani, 2016). Several authors have reported that preharvest spraying (20 days before harvesting the bulbs) of Wylom OP at 1000 mg kg $^{-1}$ and Mepiquat chloride at 500 mg kg^{-1} controlled postharvest losses (rotting, sprouting and physiological weight loss) and maintained the quality of onion bulbs during storage (Biswas et al., 2010; Chope et al., 2012; Vethamoni & Gomathi, 2018). In addition to preventing the physiological changes in bulbs, pre-harvest spraying (before 30 days) of MH at 2000 mg kg^{-1} along with fungicide (carbendazim at 1000 mg kg^{-1}) significantly reduced rotting in bulbs during storage (Kumar et al., 2015). Preharvest chemical treatment coupled with effective post-harvest management such as cold storage, storage under controlled atmosphere and gamma irradiation inhibited rotting, sprouting and rooting and enhanced the shelf life of onion bulbs. A list of recommended pre-and postharvest practices in onion bulb production is listed in Table 2.

7. Processes involved in post-harvest storage of onion

In agriculture, post-harvest treatment involves handling crops immediately after harvest, which includes cleaning, sorting, grading, and preservation. The shelf life and storability of onions are influenced

Table 2
Pre- and post-harvest practices of onion.

Sr. No.	Treatment name	Chemical used	Optimum dose	Maximum Residue Levels	Observation	References
Physical Method						
1.	Irrigation		225 to 1040 mm water supply		• Irrigation usually stopped 2 weeks before harvesting • Excessive irrigation increases rotting and sprouting during storage	Muhie, 2022
2.	Fertilizer	Nitrogen	100-200 kg ha^{-1}		• Usage of nitrogen upto 200 kg ha^{-1} affect significantly as it increases bulb size and weight • Nitrogen > 200 kg ha^{-1} reduces bulb storability becoming susceptible to rotting and sprouting during storage	Kumar et al., 2007 Petropoulos et al., 2017 Islam et al., 2019
		Potassium (K_2O)	75-100 kg ha^{-1}		• Usage of Potassium in field (75-100 kg ha^{-1}) resulted maximum plant growth, sound bulb • Excess usage of potash in field tend to weight loss and sprouting percentage in onion bulb.	Coolong, 2007
		Sulphur	50 kg ha^{-1}		• Application of sulphur enhanced production of flavour precursors such as S-alk(en)yl-L-cysteine sulfoxides • Improved flavour and aroma of onion bulbs	
		Calcium ($CaCl_2$)	115-230 kg ha^{-1}		• Helps in strengthening of cell walls and inhibit microbial infections. • Increase bulb firmness with supplementation while decrease with storage • Onion pungency decreases with excess dose	
Chemical Methods						
1.	Fungicide	Methyl *N*-[1-(butylcarbamoyl) benzimidazol-2-yl] carbamate (Benomyl) and 3-(3,5-dichlorophenyl)-1,5-dimethyl-3-azabicyclo [3.1.0] hexane-2,4-dione (Procymidone)	0.2%	**Benomyl**- 0.01 mg kg^{-1} (0.05 mg kg^{-1} when testing at 0.01 mg kg^{-1} not possible) **Procymidone**- 0.2 mg kg^{-1}	Spay of benomyl and procymidone helps in reduction of onion neck rot disease during storage.	Tripathi, & Lawande, 2019
		Methyl benzimidazol-2-ylcarbamate (Bavistin) and 1H-1,3-benzodiazole (Benomyl)	0.1 % respectively	0.1-0.2 mg kg^{-1} Sum of benomyl and carbendazim expressed as carbendazim	The combined spray of bavistin and benomyl helps in decay losses in onion. The spray of Bavistin controls *Aspergillus niger* growth.	
2.	Growth regulator	Maleic hydrazide (MH) 1,2-dihydro-3,6-pyridazinedione	1500-2500ppm 8–12 L ha^{-1}	15 mg kg^{-1}	The use of maleic hydrazide before harvesting for 2-4 weeks reduces sprouting during storage. Increases the shelf-life of onion Works like growth regulator or retardant and helps in inhibiting sprouting and rooting of onion.	Tripathi, & Lawande, 2019 Muhie, 2022 Adamicki, 2004
3.	Growth retardant	Chlormequat chloride (Wylom OP)	1000 mg Kg^{-1}		Spray of Wylom OP 20 days before harvesting reduced post-harvest.	Muhie, 2022
4.	Sprout suppressant	Ethylene and 1-Methylcyclopropene (1-MCP)	Ethylene (10 µl L^{-1}) and 1-MCP (1 µl L^{-1})		• Usage of Ethylene in combination with 1-MCP at 6°C storage reduces the respiration rate resulted in sprout suppression. • Treatment with 1-MCP at 20°C for 24h penetrate onion skin and affect meristematic growing point (sprout initiation point), reduces carbon utilization in onion bulb • Increase fructose content 2 time than untreated onion bulb	Chope et al., 2009 Cools et al., 2011
		Ethanol and 2-Chloroethylphosphonic acid (Ethephon)	2% (Ethanol) and 1 % (Ethephon)	Ethephon- 0.05 mg kg^{-1}	• Usage of 2% ethanol limits weight loss and sprouting to 14-20% and 4-6% respectively • Ethephon treatment delayed postharvest loses up to 2 month of storage period • During storage of 2-4 month shows decrease in sugars and flavonoid while increase in phenol, vitamin-c and protein content.	Murkute & Anandhan, 2016
		Ethanol and potassium sorbate	Ethanol (71.08 % v/v) and		• The combination of ethanol and potassium sorbate reduces the physiological weight losses and	Guha and Basak, 2013

(continued on next page)

Table 2 (*continued*)

Sr. No.	Treatment name	Chemical used	Optimum dose	Maximum Residue Levels	Observation	References
			Potassium sorbate (0.76% w/v)		rotting for storage up to 90 days at 30 ±2°C with relative humidity 73±2 % RH	

Maximum residue limits (MRL) for different chemical agents have been obtained from European Food Safety Authority (https://efsa.onlinelibrary.wiley.com) (Accessed on 15-08-2024)

by factors such as cultivar, growing environment, harvesting severity, postharvest drying, storage conditions, and storage duration (Brewster, 2008). Improper harvesting techniques, such as early harvesting or harvesting immature bulbs, can increase moisture content, leading to physical damage, microbial contamination, sprouting, and weight loss in onions. Improper harvesting practices contribute to 4-12% of crop losses in onions (Elik et al., 2019; Yeshiwas et al., 2023). Further upon harvesting, the chemical composition of onion undergoes changes due to the increased rate of respiration. Among the various metabolites present in onion, quercetins and its derivatives have high nutritional significance owing to its wide range of nutritional benefits. Improper harvesting and topping affect the quercetins content in onion bulbs. Early lifting and injury during harvesting results in reduced quercetins levels in onion bulbs (Mogren et al., 2006). Further improper field curing conditions and storage results in quercetins deterioration. Proper maintenance of temperature, humidity and light exposure is essential for obtaining sound bulbs with higher quercetins levels (Ren et al., 2020). Physicochemical treatments such as drying, chemical fumigation, and exposure to radiation are few commonly adopted practices in post-harvest management of onions.

7.1. Onion storage practices in India

Conventionally, onions are stored in farm sheds or structures made from locally available materials such as bamboo structures. Onions are stored by spreading on floor under ambient conditions requiring large base area. In certain regions, onions are spread on rice straw or saw dust (Kiran et al., 2024). Onions are typically stored in heap pattern. However, this results in reduction in firmness of the bulbs due to the heavy pressure exerted by the upper bulbs on the bottom ones. Zewdie et al. (2022) reported that storage in heap pattern results in significant losses (40-50%) of the total produce. The temperature range observed in the conventional Indian storage structures range between 18-35°C while the humidity range between 67-77% RH. These conditions were higher compared to the ambient conditions (10-34°C and 57-68% RH) resulting in higher losses (Dabhi et al., 2008). The low ventilation, high humidity and inability to control temperatures in the traditional storage structures lead to higher percentage of rotting and sprouting (Tripathi et al., 2016). Further, lack of aeration and inefficient air movements in the structures limit the uniform application of chemical fumigants for controlling the microbial infestation and rotting. Apart from the heap structures, other storage types include ventilated structures such as kandha chawl (ventilated hut) with locally available materials. However, there is no control of temperature and humidity in these structures. Other structures include bottom ventilated thatched roofed bamboo huts, galvanized iron-based structures. The major challenges with these traditional structures include low durability and strength, lack of temperature and humidity control, high risk of microbial contamination and low storage duration, ideal inly for on-farm storage (Kiran et al., 2024; https://doca.gov.in/goc/assets/document/Grandchallenge-Document.pdf). The ideal conditions recommended for long term storage of onion bulbs with minimal losses are temperature (25-30°C) with humidity between 60 and 65% RH for ambient conditions and temperature between 0 and 5°C with humidity in the range of 65-70% RH under cold storage conditions (Naqash et al., 2022; Kiran et al., 2024).

Temperature critically affects the rate of respiration in onion bulbs. Bulbs stored at colder conditions had slower respiration compared to the ones stored at room temperature (Rahmah et al., 2023). Further increase in temperature promoted sprouting in onions. It was observed that the rate of sprouting was highest between 17 and 25°C while nearly zero when onions were stored below 5°C. According to Adamicki (2004), low temperature storage (0°C) reduces the sprouting by 44.4% during long term storage of onion bulbs. Further to sprouting, the dry matter loss was higher at temperatures between 17 and 25°C as a consequence of the respiration. This is required to mobilise material stored in the scales towards breaking of dormancy and growing sprouts (Brewster, 1987). Similar observation was made by Yoo et al. (2013) who reported an increased respiration rate, sprouting and shoot growth at temperatures ranging between 13 and 20°C whereas storage at low temperatures i.e., 0-5°C at 60-75% RH showed significantly no physiological changes. Further, sufficient ventilation during cold storage reduced the microbial infection by 10-20% (Ji et al., 2018). Storage at temperatures >25°C inactivates enzymatic activity of bulb but increases respiration and deteriorates the quality of onion bulbs (Petropoulos et al., 2017). Current storage systems practiced in India require significant improvement in handling efficiency for long term storage with minimal losses. This necessitates development of alternative storage strategies such as cold storage or controlled atmosphere conditions and other novel techniques.

7.1.1. Cold storage of onions in India

Studies on effect of cold storage for Indian varieties are limited. In a study by Tripathi & Lawande (2019), storage of onion cv. N-2-4-1 at temperatures ranging from 0-2°C at 60-65% RH resulted in minimal losses (5-6%) after 4 months of storage unlike ambient conditions where crop loss was 7-folds higher with 34-35% loss. Further rotting due to microbial infection was nearly zero under cold storage while under ambient conditions, the percentage rotting was nearly 11% (Tripathi & Lawande, 2019). Research done by Abbas & Ali (2013) concluded that, the minimum percentage of weight loss (6%), sprouting (9.6%) and rotting (1.7%) was recorded in cold storage (4°C) whereas the maximum weight loss (98%), sprouting (100%) and rotting (70%) was observed in cemented stored room. It has been observed that cold storage does not degrade the concentrations of bioactive metabolites, mainly flavonoids. Sharma and Lee (2016) observed a of lower rate of degradation of quercetins and higher sugar content under cold storage (4°C). However, anthocyanin content was affected during cold storage (2°C) in red onions (Ren et al., 2020).

Although cold storage has significantly reduced the issue of spoilage (rotting and sprouting), there are certain challenges associated with it. Some critical aspects that need attention are freezing injury, ammonia injury and post cold storage sprouting. Care must be taken not to expose the bulbs below -2°C and ammonia gas leakage inside the cold chamber. These result in weight loss and bulb deterioration such as browning and pungency. Transition to ambient conditions after cold storage results in sprouting due to increased respiration under higher temperatures. This necessitates alternative treatment involving chemicals or novel physical, athermal treatments (Tripathi & Lawande, 2019).

7.2. Physical treatments

7.2.1. Artificial and fast curing

In artificial curing, forced convective air is circulated using a blower in the temperatures ranging between 24 and 29.5°C with moderate humidity (60-65% RH) and 25000 cm^3 /sec per m^3 of onions. In certain conditions, the curing temperature is increased up to 35°C depending on the variety and number of layer of bulbs. Onion bulbs are dried till the moisture is reduced by 3-5%, neck is dried and outer scales become brittle (Gorreapti et al., 2017; Naqash et al., 2021b). Artificial curing is more suitable for onions harvested during autumn season when unexpected rainfall occurs in India. Artificial curing at aforesaid temperatures have been reported to extend the shelf life of onions by 6 months. The optimal conditions for forced curing are temperatures ranges between 25-30°C for 10 days at moderate humidity (60-65% RH) to improve the storability of onions. However, excessive heating during curing results in desiccation of bulbs (Muhie, 2022). In cases of prolonged wet weather during onion harvesting, artificial curing at temperatures between 32-34°C can accelerate the process and reduce the risk of neck rot (Lacy & Lorbeer, 2008). High humidity (>70% RH) and temperatures (>32°C) can cause rotting while high temperatures (>32°C) and low humidity (<60% RH) result in weight loss and bulb desiccation (Gorreapti et al., 2017; Kiran et al., 2024).

Alternatively, Eshel et al. (2014) developed a fast-curing process using an ultrasonic fogger at 30°C and 98% RH, which dried the outer scales of the bulbs quickly. The authors treated the onion bulbs for 3-9 days under aforesaid conditions and stored the bulbs at 2°C at 70% RH for 10 months. The authors observed that fast curing technique reduced the incidence of neck rot and inhibited early sprouting in bulbs, making it suitable for immature onion bulbs with green longer necks. This is because, early harvested bulbs with longer necks are prone for microbial contamination as outer layers of bulbs are fleshy owing to higher moisture content (Brewster, 2008). The fast-curing technique is effective in degrading parenchyma cells leading to faster drying of the outer skin, inhibition of early sprouting and improved resistance to microbial contamination like neck rot disease. However, the authors observed that fast curing technique was more suitable for long neck varieties as they have better ability to seal themselves from microbial penetration compared to shorter necks. The technique is more suitable for very hot and dry climates to prevent surface cracks caused by desiccation during open curing.

7.2.2. Light

Growth and development of onions bulbs is affected by daylength, light quality and light interception. It has been observed that during short days, no bulbs are formed; while in long days, large bulbs are formed, but time taken to maturity is longer; and in very long days, small bulbs are formed which mature quickly (Bertaud, 1986). Exposure to longer daylight during curing has been beneficial by improving the nutritional quality of onions. Curing under field conditions at 24°C leads to the enhancement of the quercetin levels by up to 40%. Exposure to light stimulates the biosynthesis of flavonoids in epidermal cells through the activation of phenylalanine ammonia-lyase (PAL) enzyme (Ren & Zhou, 2021). The presence of quercetins prevents the onion bulbs from damages caused due to UV exposure. Furthermore, exposing the cured onion bulbs to different light wavelengths such as blue, red, UV light, and white fluorescent light increases the quercetins content (Sagar et al., 2022). Exposure to blue light resulted in maximum quercetins accumulation while UV light inactivates pathogens on the bulbs (Ko et al., 2015).

7.2.3. Control atmospheric Conditions

Controlled atmosphere (CA) storage has been practiced widely for climacteric type of fruits and vegetables. Although onions are non-climacteric type, they still undergo physiological changes after harvesting such as sprouting and rooting and importantly susceptible to rotting. The main objective of CA storage is to slow down the respiration and it is achieved by altering the composition of atmospheric gases, mainly O_2 and CO_2 in the storage chambers. Higher atmospheric O_2 levels in the storage chambers significantly influence the sprouting and rooting process in onions and also fastens the breakdown of fructans and loss of TSS in bulbs and increases pungency and bad odour (Tanaka et al., 1996; Petropoulos et al., 2017). Adamicki and Kepka (1973) reported that storage of onion bulbs under 5% CO_2 and 3% O_2 resulted in highest percentage of bulbs with marketable quality. Similarly, storage of onion bulbs under low O_2 levels and higher CO_2 levels inhibited rooting and sprouting in onion bulbs with extended storage life when compared to bulbs stored under ambient conditions. Storage of bulbs at 1% O_2 and 1% CO_2 with N_2 as the remainder between 0°C and 1°C resulted in best quality attributed to the imposed dormancy and maintenance of innate dormancy in onion bulbs (Tanaka et al., 1996). In another study, use of growth regulator maleic hydrazide in combination with CA storage (3% CO_2 and 0.5% - 2% O_2 reduced sprouting and rooting in bulbs during long term storage (Muhie, 2022). Storage under CA conditions (1% O_2 and 1% CO_2, 2.5°C and 60–75% RH) resulted in lower pungency (low pyruvic acid) in onion bulbs, higher carbohydrate content and also reduced microbial load resulting in reduced deterioration due to microbial activity (Rios-Gonzalez et al., 2018).

The inhibition of sprouting in onions under controlled atmosphere conditions could be attributed to the modulation of abscisic acid (ABA) concentration. The ABA concentration exponentially decreases in onion bulbs after harvesting and is concomitant with decline in storage potential of the bulbs. Storage under controlled atmosphere conditions reduce the rate of decline in ABA levels, rather degradation of ABA, leading to enhanced storability (Chope et al., 2006). Further, storage under controlled atmosphere with higher CO_2 and lower O_2 levels reduces the activity of alliinase enzyme that cause hydrolysis of S-alk(en) yl-l-cysteine sulphoxides (ACSOs) to pyruvates leading to lower pungency when compared to storage under ambient conditions (Uddin and MacTavish, 2003). The most optimum gas concentration for long term storage of onion bulbs under CA conditions resulting in best quality are 1-3% of both CO_2 and O_2 at temperatures ranging between 2.5 and 4°C (Tanaka et al., 1996; Rios-Gonzalez et al., 2018). However, the storage conditions may vary between different onion varieties necessitating prudent optimization.

However, long term storage at higher levels of CO_2 (>5%) coupled with very low temperature resulted in internal spoilage of bulbs due to anaerobic respiration (Chope et al., 2006; Rios-Gonzalez et al., 2018). Further long-term storage under CA conditions may affect the quality of onion bulbs when transitioned to ambient storage conditions. Removal of bulbs from CA storage resulted in an immediate increase in the respiration rate triggering the onset of sprouting (Chope et al., 2007). The authors observed that delaying the storage of onions under CA conditions by 21 days after harvest resulted in enhanced storability and stable transitioning when compared to storage under CA conditions immediately after harvest.

7.2.4. UV irradiation

Ultraviolet (UV) irradiation, specifically UV-C radiation have been utilized for sterilization of onion bulbs. The wavelength range 250-260 nm have been found to be lethal for pathogens causing spoilage of onion bulbs. Treatment of onion bulbs with UV-C at a dose of 2 kJ m^{-2} enhanced the storage life of bulbs. Further exposure to UV radiation suppressed sprouting and prevented weight loss in onion bulbs. In addition, the UV treated bulbs had relatively higher dry matter, total soluble solids and phenolic contents compared to untreated bulbs (Ionica et al. 2022). UV irradiation ranging between 1.2 and 6 k J m^{-2} were effective in controlling the microbial growth in onion, specifically peeled and cut onions (Rodov et al., 2010). The authors artificially inoculated the onions with microorganisms such as *E. coli* and *Penicillium* spp., and observed that UV-C irradiation reduced the microbial growth by 1.5-3 logs and improved the shelf life of onions. Further the authors observed that exposure to UV-C irradiation increased the total flavonol content and antioxidant capacity of peeled onions (Rodov et al., 2010). In another study, exposure of onion bulbs to UV-C radiation followed by storage at 5°C at 85-90% RH for 15 days did not induce any decay, weight loss and rooting. Meanwhile, control, untreated samples showed significant levels of microbial decay and dry matter loss (Kasim & Kasim, 2010). The authors observed that exposure of bulbs (specifically peeled onions) to UV-C radiation for 15 mins or beyond caused electrolyte leakage and yellowing of bulbs. However, exposure of bulbs to UV-C radiation for shorter period (<10 min) resulted in the enhancement of phenolics content and antioxidant capacity (Kasim & Kasim, 2010). Thus, UV treatment can be exploited for simultaneous decontamination and enhancement of nutritional quality of onion bulbs.

7.3. Chemical treatments

7.3.1. Fumigation

Fumigation is a traditional method used for elimination of micro-organism with gaseous fumigants such as phosphine by its precursor aluminium phosphide, methyl bromide, ethylene oxide, propylene oxide, and sulphur gas fumigation. Due to environmental concerns, methyl bromide has been banned for soil application for agricultural produce and have not been recommended for quarantine and pre-shipment phytosanitation (https://www.unep.org/ozonaction/what-we-do/methyl-bromide). Metallic phosphides and sulphur gas fumigation have been found effective in the control of pathogens. Sulphur gas (SO_2) fumigation at an application rate of 50 g m^{-3} for up to 5 hours has been shown to reduce black mold infection in onion bulbs (Srinivasan & Shanmugam, 2006; Tripathi & Lawande, 2019). Sulphur powder is the commonly used for fumigation purposes. Heating of sulphur powder generates sulphur-di-oxide (SO_2) which in turn acts as disinfectant.

7.3.2. Ethylene treatment

Exogenous ethylene treatment in gaseous form during onion storage has been found useful in inhibiting the sprouting in onion bulbs. Bufler et al. (2009) reported that continuous application of ethylene at 7-10 μl L^{-1} throughout the storage had reduced sprouting in bulbs. In another study, exposure of onion bulbs to ethylene (10 μl L^{-1}) for 24 h at 20°C reduced the sprouting in onions when stored up to 31 weeks at 1°C (Downes et al., 2010). However, continuous exposure to ethylene during long term storage is difficult, necessitating short term treatments. In this context, Cools et al. (2011) reported that use of 1-methylcyclopropene (1-MCP), a ethylene site binding inhibitor, at 1 μl L^{-1} concentration along with ethylene (10 μl L^{-1}) resulted in reduction of sprouting.

The authors reported that ethylene + 1-MCP treatment after curing could be a cost-effective solution in preventing sprouting in onion. However, treatment before curing resulted in enhanced respiration rate causing premature sprouting (Bufler, 2009). In addition to the inhibition of sprouting, ethylene + 1-MCP treatment increased fructose content by two-folds thereby modulating TSS content (Downes et al., 2010). Ethylene + 1-MCP treatment offers an alternative solution to the use of chemicals and sprout suppressants like maleic hydrazide during pre-harvest stages, which leaves detectable residues in the bulbs (4-6 mg kg^{-1}) (Johnson, 2006).

7.3.3. Antimicrobials and fungicides

Microbial contamination, particularly fungal rot, causes 15-30% of losses during onion storage (Kumar et al., 2015). Various microorganisms like *Aspergillus* spp., *Penicillium* spp., *Alternaria* spp., *Fusarium* spp., *Rhizopus* spp., *Colletotrichum* spp., *Pseudomonas* spp., *Erwinia* spp., and *Botrytis* spp. are responsible for rot in onion bulbs (refer section 5.1). Foliar application of fungicides 10-15 days before harvesting of bulbs significantly reduce the pathogen load and helps in reduction of diseases during storage. Some commonly utilized fungicides are carbendazim, bronopol, mancozeb, blitox, dithane-M45, salicylic acid, bavistin, are commonly used for long-term onion storage (Tripathi & Lawande, 2019).

Black mold is a significant disease affecting onions, causing substantial economic losses. Pre-harvest application of fungicides such as bavistin (0.1%), difoliton, blitox, and dithane-M-45 inhibited *A. niger* during long term storage (2 months) of onion cv. Hisar-2 variety (Maheswari et al., 1988). Pre- and post-harvest spray of carbendazim have been found effective in controlling microbial rotting and decay of bulbs. In a study conducted by Singh & Sharma (2002), spraying of 0.1% carbendazim at 100 and 110 days after planting of onion variety Agrifound Dark Red was effective in preventing rotting and physiological weight loss. Kumar et al. (2015) observed that spraying of carbendazim at regular intervals reduce the disease incidence by over 90% even after 90 days of storage.

Fusarium basal rot is another destructive disease causing significant economic losses, with post-harvest mature stages being the most susceptible. Treatment of seeds with carbendazim and propineb (zinc containing dithiocarbamate) at 10 g kg^{-1} prevented seed damage (Bektas & Kusek, 2021). Additionally, use of quaternary ammonium compound-based antimicrobials (Granosan 200), benzimidazole based fungicides (Benomyl), and broad spectrum dithiocarbamate based fungicides (mancozeb) reduced disease incidence significantly and also improved crop yield (Akhtar and Javaid, 2018). Various fungicides like azoxystrobin + difenoconazole, fluopyram + trifloxystrobin, fluazinam, and difenoconazo*le have shown potential in controlling *Fusarium oxysporum* f. sp. *Cepae* (Akhtar and Javaid, 2018). For the control of purple blotch, dimethylcarbamothioic dithioperoxyanhydride (Thiram®) at 0.25% has been found effective (Tripathi and Lawande, 2019). Use of fungicides such as tebuconazole, fluopyram, mancozeb and carbendazim at concentrations of 250 mg kg^{-1} inhibited nearly 86%, 71%, 61% and 21% of mycelial growth respectively (Jhala et al., 2017). Spraying mancozeb, chlorothalonil, or iprodione at fortnightly intervals reduced the disease occurrence significantly in onions (Tripathi & Lawande, 2019). Likewise, significant reduction in the incidence of neck rot was achieved by treating the seeds with fungicides such as bavistin or benomyl before sowing and spraying of benomyl and procymidone at 0.2% before the harvesting of bulbs. Additionally, spraying carbendazim at 0.2% before harvesting prevented the spread of neck rot and improved the post-harvest storage of onions (Tripathi & Lawande, 2019).

7.3.4. The challenge of chemical residues in Onion

The adverse effects of chemical fungicides and pesticide residues on the environment and human health have raised significant public concern, particularly with chemical fumigants. Residues of fumigants exceeding their threshold levels can lead to toxic effects such as acute neurological defects, immune system disturbances, reproductive system irregularities, and other life-threatening diseases (Ahmad et al., 2024). Farmers typically practice cultural treatments after harvest and before storage as fumigation is an expensive process. Propiconazole, a 14α-demethylation inhibitor, is an effective triazole fungicide widely used in the agricultural industry for its broad-spectrum antifungal actions against pathogens (Calonne et al., 2012). It is used to control fungal diseases such as black spot, grey mould, and powdery mildew on fruits, vegetables, and other field crops. The safe application of propiconazole involves calculating dietary exposure and assessing the risk using the risk quotient (RQ) method. An RQ value below 100% indicates safe human exposure and consumption, while a value above 100% indicates unacceptable and adverse effects on human health (Bai et al., 2021).

The use of organochlorine pesticides has been banned worldwide due to their toxicity. Frequent exposure to organophosphate pesticides is linked to reduced acetylcholinesterase activity, haematological alterations, liver and renal dysfunctions (Kapeleka et al., 2020). Therefore, there is a need for novel processing techniques that can effectively decontaminate without leaving chemical residues. Alternatively, use of biofungicides/phytofungicides have been suggested for controlling fungal diseases in fruits and vegetables (Fenta & Mekonnen, 2024). In addition, use of biofumigants within a limited range such as thymol have been recommended as they do not leave any residues and have been identified to be safe for human consumption (Ji et al., 2018).

7.3.5. Biofungicides in onion production

Biological treatments effectively control spoilage microorganisms in onions by using competitive microorganisms like *Trichoderma*. Trichoderma is a common biocontrol agent that inhibits plant pathogenic fungi (Akthar & Javaid, 2018). Other bio agents such as *Pseudomonas* spp., and *Bacillus subtilis* can reduce the infection probability of *F. oxysporum* f. sp. cepae by 85% (Savitha et al., 2022). Studies by Yadagiri & Gupta. (2017) have shown that treatments with gibberellic acid (GA3) at 100 mg kg^{-1} + *T. viride* at 10 kg ha^{-1} soil can significantly increase bulb yield and reduce the incidence of fungal rot. *Brevibacillus* is used for biological treatment of basal rot caused by *F. oxysporum* f. sp. cepae by secreting edeine, a cationic peptide that inhibits host translation mechanism (Johnson et al., 2020). Microorganisms like *Trichoderma* spp., *Bacillus* spp., and Arbuscular mycorrhizal fungi (AMF) have been used as biofungicides against white rot disease caused by soil-borne fungus *Sclerotium cepivorum* Berk. (Gebretsadkan et al., 2020; Amin & Ahmed, 2023). Extracts from *Eucalyptus tertonia* and *Azadirachta indica* are effective in preventing soil-borne fungal diseases such as black mold caused by *Aspergillus niger*. Extracts from plants such as *Imperata cylindric*a, *Raphanus sativus*, and *Acacia nilotica* have antifungal activity against pathogens like *Macrophomina phaseolina, Fusarium oxysporum* f. sp. lycopersici, and *Sclerotium rolfsii*. Spraying *Azadirachta indica* (neem) oil at a 3% concentration, twice, once at the onset and then fortnightly, can inhibit leaf blight disease development, increase the yield and improve crop storage (Awurum et al., 2016).

8. Novel techniques in Onion processing

Novel storage techniques are methods that aim to improve the preservation, quality, functionality, and value of crops like onion.

8.1. Gamma Irradiation

Radiation treatment of by gamma rays has emerged as a potential and commercially viable option for post-harvest management of onion bulbs, specifically the inhibition of sprouting (Tripathi et al., 2011). Onion bulbs are metabolically active and under ambient storage conditions (18-25°C temperature with >85% relative humidity) bulbs undergo sprouting. Application of gamma irradiation completely inhibited the sprouting (100% inhibition) by disrupting the genetic makeup. Further, they controlled the loss of solids content in bulbs and extended the shelf life up to 9 months (Akhther et al., 2022) The application of irradiation treatment is generally performed by use of ^{60}Co, as gamma source at dosage ranging from 10 to 200 Gy (Sharma et al., 2020). The Onion has a relatively higher dormancy compared to other crops and this causes loss of TSS over the storage period. Exposure to gamma rays reduced the TSS loss by up to 30% during 4–6-month storage at ambient temperature (Tripathi et al., 2011). The most optimum level of gamma irradiation was found to be 120 Gy which resulted in minimal physiological loss *viz.*, loss of weight (18%), rotting (3.5%) and sprouting (0%) up to 84 days in an ambient storage (Sharma et al., 2020). The authors reported that the marketable quality of onions such as colour and aroma and were maintained up to 3 months after gamma irradiation. Firouzi et al. (2021) reported that use of electron beams (1.25 MeV) and gamma rays at 200 Gy completely eliminated the microbial contamination along with retention of vitamins such as B3, B6, and vitamin C. Although highly beneficial, high dose of gamma rays (1.0 – 1.5 KGy) cause physiological damages to the onion bulbs such as electrolyte leakage owing to cellular membrane damage (Memon et al., 2020). The authors reported that a combination of gamma irradiation at 1.0 KGy and use of food grade preservatives such as sodium benzoate (0.1% w/w) was found to be the best in terms of retention of sensory and phytochemical properties of onion bulbs. Apart from the spoilage aspect, gamma irradiation also improved the nutrient quality of onions by enhancing the concentration of volatile compounds and polyphenols (Kavita et al., 2024). The authors reported 1.5 folds in the organo-sulphur compound, 25 folds increase in the quercetin content and 1.5 to 2 times enhancement in antioxidant property of onions when irradiated at 200 Gy after 105 days of storage at ambient conditions. In addition to the treatment of bulbs, gamma irradiation has been used for the treatment of minimally processed ready to eat cut onions and onion rings. Sharma et al. (2022) reported that exposure of onion rings to radiations at 0.5 to 2.5 KGy resulted in complete inhibition of microbial growth. The authors identified an optimal dosage of 1.5 KGy for preserving the nutritional and sensory quality of minimally processed onions. However, exposure to high doses of radiation (2.5 KGy) resulted in the reduction of physicochemical properties such as increased weight loss (by 22%), increased TSS content, decreased ascorbic acid and organo-sulphur concentration (by up to 40%) in the minimally processed onions. The authors reported that hydrolyzation of fructans upon exposure to high dosage of gamma irradiation caused the increase in TSS and loss in quality similar to the observation made by Memon et al. (2020). In another example, exposure of cut onions to 60 Gy followed by low temperature storage conditions (4°C - 6°C, RH 65-70%) did not result in the growth of any harmful microorganisms such as *Salmonella* sp. and help retain moisture of the freshly cut onions up to 30 days (Khade et al., 2023). According to Food Safety Standards Authority of India (FSSAI), the maximum permissible dose of gamma irradiation for onion bulbs is 0.2kGy. Onions are classified under class 1 food products consisting bulbs, stem, root tubers and rhizomes. FSSAI recommends the application of gamma irradiation mainly to inhibit the sprouting in bulbs with a dose limit for class 1 food products between 0.02 and 0.2 kGy (FSSAI, 2022). Thus, gamma irradiation can offer an excellent option for long term storage of onions under ambient conditions as an alternative to energy intensive cold storage.

8.2. Cold plasma treatment

Cold plasma is a contemporary, non-thermal technology for food decontamination, food quality improvement such as toxin degradation and surface modification (Pankaj & Keener, 2017). Cold plasma refers to quasi-neutral ionized gases that are composed of electrons, photons, and free radicals that are net neutral in their charge (Pankaj & Keener, 2017). They are generated by external photoelectric effect or through collision of electrons (Filipić et al., 2020). Cold plasma has been identified as an ecofriendly technique for variety of agriculture applications such as enhancement of plant germination, development and resilience to illness (Gao et al., 2022). In addition to these, cold plasma has been used for sterilization of seeds through microbial decontamination (Mandal et al., 2018). A study by Kopacki et al. (2017) indicated that cold plasma treatment of onion seeds resulted in reduction of microbial contamination. The authors used helium and air mixture for generation of plasma at 45 W power, 0.42 kV of voltage and 14.72 MHz frequency using a radio frequency jet type reactor at atmospheric pressure. The seeds were exposed to cold plasma from 60 s to 480 s, and it was observed that fungi such as *Alternaria alternata, Penicillium* sp., *Trichoderma harzianum* and *Fusarium oxysporum* were inhibited after cold plasma treatment. Cold plasma technology has been extensively used in decontamination of food products such as onion powder and flakes. It has been observed that helium cold plasma treatment of onion flakes at 15 KHz for 20 min resulted in the significant reduction of microbes such as *Salmonella enterica, Escherichia coli*, and *Listeria monocytogenes*. Plasma treatment did not affect the color, surface morphology, moisture and polyphenol content, specifically quercetin (Kim & Min, 2018). Similar observation was made by Kim et al. (2017). who reported decontamination of onion powder with high microwave density - cold plasma treatment (HMCPT). The authors observed a significant reduction in pathogens such as *Bacillus cereus, Aspergillus brasiliensis* and *E. coli* without any negative impact on the colour and antioxidant activity when the onion powder was exposed to HMCPT at 400 W and 40 min.

Besides the reduction of microbial load, cold plasma treatment did not affect the chemical composition and the antioxidant potential of onions. The quercetin and quercetin glycosides levels were statistically similar (60 – 68 mg 100 g^{-1}) between fresh untreated and cold plasma treated samples indicating the retention of antioxidant compounds after HMCPT (Kim et al., 2017). Further the authors observed that cold plasma treatment did not affect the DPPH free radical scavenging potential of the onion when compared to fresh, untreated samples. More recently, cold plasma treatment was found effective against microorganisms which are resistant to chlorine disinfectants (Kazemzadeh et al., 2022). The authors exposed onion rings contaminated with *Salmonella enterica* with atmospheric cold plasma from 5 min to 15 min at different voltages (6, 8 and 11 kV) and observed a 3 log CFU/g reduction in bacterial cells when exposed to plasma at a voltage of 6 kV for 5 to 10 min. Thus, cold plasma could be effective in non-thermal decontamination of microorganisms that cause spoilage as well as enhance the shelf life of value-added products without losing the nutritional and sensory attributes (Sruthi et al., 2022).

8.3. Ozonation

Onion bulbs can be preserved long term in cold storage along with gaseous ozone treatment, as an alternative to other traditional methods. Ozone (O_3) is triatomic molecule of oxygen, highly unstable, reactive and is a powerful disinfectant owing to its strong oxidation properties. Corona discharge to atmosphere (air) generates gaseous ozone, which are used either in gaseous or aqueous form for post-harvest treatment of fruits and vegetables (Shelake et al., 2023). Ozone has been used for disinfection of a range of fruits and vegetable such as kiwi, strawberry, pear, apple, carrot, chillies, mango and banana (Shezi et al., 2020). There are very few studies conducted on the impact of ozone on onion quality. Lim et al. (2021) treated onions with ozone at 1 mg kg^{-1} and observed a significant reduction in the total count of bacteria, specifically a 4 log (CFU g-1) reduction of aerobic bacteria *Rahnella aquatilis* and 0.9 log of yeast and mold in onions bulbs stored at 2°C, 70% RH for 2 months. Although, ozone is a strong oxidizing agent, there was no significant changes on the colour and firmness in comparison to control (Lim et al., 2021). In a recent study, Shelake et al. (2023) evaluated the effect of ozone treatment on onion quality parameters such as pungency, colour and antioxidant potential. Continuous exposure and high concentrations of ozone reduced the pungency factors. Further the authors observed a concentration dependent reduction in ascorbic acid and pyruvic acid content. On the contrary, the antioxidant potential of onions improved upon ozone treatment with increase in total phenolics, flavonoids and anthocyanin content. The concentration of antioxidant molecules and DPPH free radical scavenging activity of ozone treated onions increased by 10% when compared to control samples. However, excess exposure to ozone (>300 ppm) resulted in decreased concentration of the phytochemicals and antioxidant capacity. The increased concentration of polyphenols upon ozone treatment could be attributed to the upregulation of shikimic acid pathway leading to higher expression of phenylalanine ammonia-lyase (PAL) and consequently the initiation of the phenylpropanoid biosynthesis (Shelake et al. 2023). this observation was made with several crops such as wine grapes, pear, apple and mango (Shezi et al., 2020). Further the strong oxidative nature of ozone causes oxidative stress on agri-produce leading to enhanced expression of endogenous enzymatic antioxidant defense such as superoxide dismutase, catalase, ascorbate peroxidase and guaiacol peroxidase (GPX) (Shezi et al., 2020).

Further ozone affects the structural integrity and physiological process of the crops owing to its strong oxidation property. Shelake et al. (2023) observed a non-significant decrease in firmness of onions upon ozone treatment. Microscopic analysis revealed the structural breakdown in the tunic layer (outer surface) upon ozone treatment resulting in a marginal decrease in colour value and anthocyanin content and damages to bulb scales at higher concentrations (Shelake et al., 2023). Experiments on other crops such as kiwi and strawberry revealed that ozone treatment delayed ripening through reduction of ethylene production by downregulating the expression of genes synthesizing key enzymes viz., 1-aminocyclopropene-1-carboxylate synthase (ACC synthase) and aminocyclopropanecarboxylate oxidase (ACC oxidase). In case of mango, ozone treatment reduced the ethylene production, respiration rate, mass loss, and delayed colour changes (Tran et al., 2013). Thus, ozone could be exploited as an alternative fumigant to sulphur fumigation for simultaneous disinfection of onions and modulation of their physicochemical properties.

8.4. Hydrogen Peroxide (H_2O_2)

Hydrogen peroxide (H_2O_2) is widely used as an alternative sanitizing agent for fruits and vegetables. Owing to their strong oxidizing property, they exhibit biocidal activity against microorganisms including bacterial endospores and protozoal cysts (de Siqueira Oliveira et al., 2018). The mechanism behind the biocidal activity of H_2O_2 are peroxidation of membrane lipids, DNA damage and inactivation of respiratory enzymes in microorganisms. Generation of hydroxyl radicals and singlet oxygen species upon treatment of H_2O_2 and consequent reaction of these free radicals with functional macromolecules (proteins, lipids and polysaccharides) in microbial cells are proposed mechanisms behind the bacteriostatic and bacteriocidal properties of H_2O_2 (Felizini et al., 2016). Microbial decontamination using H_2O_2 are generally achieved with concentrations ranging from 2.5% to 20% of the fresh weight of the agro-produce. H_2O_2 treatment has been found to strongly inhibit food pathogens such as *Clostridium* sp., *Listeria monocyteogenes, E. coli, Salmonella* sp., and coliforms in vegetable such as bell pepper, strawberries, watercress and fresh cut melons (Ukuku et al., 2005; Alexandre et al., 2012). H_2O_2 have been utilized as effective alternative to chlorine treatment and 2.5% H_2O_2 solution have been found to be effective equivalent to 200 mg kg^{-1} of chlorine treatment (Ölmez and Kretzschmar, 2009). The biggest advantage with the use of H_2O_2 is the non-toxic nature and high instability of the molecule. H_2O_2 decomposes to water and oxygen upon exposure to catalase and peroxidase enzyme and water (Alexandre et al., 2012; Felizini et al., 2016). Thus, the excess concentration of H_2O_2 can be easily removed by rinsing the treated material with water immediately after exposure treatment thus preventing alterations to the sensory properties of the produce. H_2O_2 is generally regarded as safe (GRAS) for food applications by FDA and have been approved for use in food processing industries (de Siqueira Oliveira et al., 2018).

In addition to decontamination, H_2O_2 have been used for breaking the endodormancy in onion bulbs during long term storage. Endodormancy is a natural phenomenon observed in onions where the plant ceases to form new leaves after the formation of mature bulbs. Conventional methods to break endodormancy involves cold shock and chemical treatments. H_2O_2 have been found to be the secondary messenger and stressor in the activation of release of endodormancy by modulating oxidative stress in the plant (Née et al., 2017). Exposure of stored onion bulbs to H_2O_2 solution (20% v/v) for 2 to 4 hours broke the endodormancy in onions and resulted in faster rooting, more uniform root development and prevented rotting of bulbs (D'Angelo and Goldman, 2019). H_2O_2 is often used in spray solutions with other disinfectants or as vapours for large-scale applications (Ukuku et al., 2005).

Large scale application of H_2O_2 for microbial decontamination of onions have not been evaluated. However, learnings from other crops such as strawberries and capsicum, reveal that over exposure to H_2O_2 impacts the sensory attributes of fruit such as colour, firmness and loss of anthocyanins (Van de Velde et al., 2016; Mani-Lopez et al., 2016). This can be attributed to the strong oxidative properties of H_2O_2 leading to change lipid and protein structures in cellular membranes affecting the firmness and sensory attributes of fruits/vegetables (Mani-Lopez et al., 2016).

8.5. Thymol Fumigation

Thymol Fumigation is another novel, ecofriendly technique for preventing fungal contamination in onion. Thymol is a natural fungicide, derived from thyme (*Thymus vulgaris)* essential oils (Borugă et al., 2014). The thyme essential oil consists *p*-cymene (8.41%), thymol (47.59%) and *c*-terpinene (30.90%) as the major ingredients showing strong anti-microbial activity. It was observed that purified thymol showed three-times stronger inhibition of microbial growth than that of thyme essential oil (Ji et al., 2018). Thymol has been shown to inhibit wide range of fungal species that infect onions such as *Botrytis aclada, Fusarium proliferatum, Penicillium* sp., *Rhizopus oryzae* and *Aspergillus awamori* (Ji et al., 2018). Spraying ethanolic solution of thymol at 30 mg L^{-1} on onion bulbs resulted in 96% reduction of disease severity caused by *Botrytis* sp. Thymol fumigation at the aforesaid concentration was much efficient in inhibiting fungal pathogens when compared to conventional sulphur treatment as demonstrated through a pilot scale trials with 200 kg onions in a cold storage facility (4°C) over a 4-month storage (Ji et al., 2018). In another study, application of thymol fumigation at 1000 mg L^{-1} concentration for 24 h significantly reduced the lesion diameter on the onion bulbs and the efficiency was at par with fluazinam, a commonly utilized fungicide control (Oh et al., 2022). The above authors concluded that thymol fumigation could control fungal disease spread at low-temperature conditions (4°C) for up to 10 months. Xu and Wu (2014), reported effective control of *Salmonella enterica* Typhimurium infection in green onions when treated with thymol and thymol formulations with citric acid, acetic acid and sodium dodecyl sulphate.

Thymol, has been utilized as a natural antimicrobial compound in various horticultural crops besides onions. Studies have shown that applying thymol at low concentrations (2-4 mg/L) or in nanoemulsion form can improve the color, flavor, aroma, and freshness of strawberry fruits for up to 12 days post-harvest by reducing the fruit dehydration (Robledo et al., 2018). Thymol treatment also helps maintain fruit firmness, cell wall integrity, and delays the degradation of membrane phospholipids and unsaturated fatty acids in blueberries during post-harvest storage (Ye et al., 2024). Encapsulated thymol in chitosan nanoparticles has been found to enhance the freshness and sensory qualities of cherry tomatoes (Álvarez-Hernández et al., 2021). Thymol is also used in the production of antimicrobial active packaging materials to extend the shelf life of fresh foods like fruits, cheese, and meat products by impregnating thymol into packaging films and polymers such as polylactic acid (PLA) and other synthetic films (Rojas et al., 2023). While there is limited research on the sensory effects of thymol on onions, findings from other horticultural crops suggest the potential for thymol to enhance the sensory and organoleptic qualities of onions.

8.6. Microwave diffusion gravity

An innovative microwave assisted technique known as microwave hydro diffusion gravity (MHG) has been evaluated for processing of onion bulbs. The technique is a modified version of conventional microwave drying where an extractor cum condenser is connected for simultaneous removal of functional components (Khan et al., 2016). The working principle of the technique involves simultaneous removal of moisture and extraction of functional components such as flavour compounds through cold water condensation. Dehydration at 400 W for 14 min was found to be the best for dehydration of onion slices to a moisture between of 20 and 25%. This technique had the least power consumption (0.3 MJ) compared to other methods such as freeze drying (3.24 MJ) and hot air drying (3 MJ). The authors reported a better texture, colour and reduced drying time for the products obtained by microwave diffusion gravity compared to conventional hot air convective drying. The authors recommended pretreatment of onion products such as slices by microwave diffusion gravity for a faster moisture reduction from 80-85% to 20-25% with improved sensory properties before further dehydration with a commercial tray drier.

Table 3

Novel techniques discussed in the previous sections have been found useful in controlling the post-harvest losses in onions. However, their large-scale adoption and utilization is dependent on the cost economics of the technology. Gamma irradiation has widely recommended for enhancing the storage of onions. The typical capital investments required for establishing a radiation facility would approximately cost between 1.5 and 2 million USD. The most important component in the facility is the radiation cell followed by storage facilities. In addition to these, operating expenses such as the cost of radiation source (^{60}Co) and electricity charges contribute significantly to the processing. Cobalt decays at a rate of 12.3% per year necessitating its replenishment at regular intervals, normally after every 2 to 3 years. The average cost of radiation source is approximately USD 1/Ci. It has been estimated that for a plant operating with a source strength of 500 kCi, approximately USD 500,000 is required towards source replenishment, otherwise called decay charges (https://www.mofpi.gov.in/sites/default/files/RPP-TECDOC.pdf.pdf). There are no clear estimates on the economics with respect to irradiation of onions in India. Khattak et al. (1999) reported that the approximate charges for gamma irradiation of onions at 0.1 KGy followed by storage at ambient conditions costed approximately Pakistan Rupees 290.00 per tonne, i.e., approximately 5-6 USD per tonne during 1999-2000. Similarly, Sharif (1990) reported that the approximate irradiation charges followed by storage at ambient conditions costed approximately USD 0.50-0.52 USD kg^{-1} onions. The calculations were based on dosage of 0.1 KGy for an irradiation capacity output of 548 Kg hr^{-1}. The author reported that the cost of cold storage of onions was nearly two-folds (0.96 USD kg^{-1}) compared to the cost of irradiation. Thus, irradiation could be a potential alternative for treatment of onions for long term storage. In case of cold plasma-based disinfection, Bhaba Atomic Research Centre, Department of Atomic Energy, Government of India has developed a sterilization device that utilizes Argon gas and deionized water for plasma generation. The device consumes very less electrical power, approximately 300 w with an input electrical supply of 240 V, 50 Hz. The approximate power consumption is 0.7 Kw for 8 hr operation. The running cost for a 10 min sterilization cycle is approximately USD 0.10. However, there are no calculations with respect to onion disinfection. (www.barc.gov.in/technologies/cpsd/index.html). With respect to ozonation, Indian Council of Agriculture Research - Central Institute of Post Harvest Engineering & Technology had developed a portable apparatus for disinfection of vegetables called Ozo-C. The equipment generates 100-200 mg h^{-1} ozone with an output air pressure of 0.2 kg cm^{-2} with an operating time between 18 and 30 min. The approximate cost of the equipment is USD 42.00 suitable for small scale applications (https://krishi.icar.gov.in/jspui/bitstream/123456789/36469/4/OZO_C_cityair_ldh.pdf).

There are no published reports on the cost economics and benefit-to-cost ratio of utilizing the novel techniques mentioned above to enhance the shelf life of onions. The main challenges in the commercial-scale implementation of these techniques include high capital investments for facility establishment and high operational expenses for generating plasma, ozone, and gamma rays. Other obstacles include incomplete control of variables for process optimization and a lack of regulatory approvals for commercial use (Jermann et al., 2015). Although these techniques are currently not commercially viable, their benefits such as producing chemical residue-free onion bulbs, extending shelf life, and ability to retain bioactive molecules like quercetin glycosides and other flavonols make them worth further exploration (Ren et al., 2020).

9. Value added products from Onion

Value addition of onions to consumer-friendly products could offer an economically viable alternative to reduce the post-harvest storage losses in India. Value-addition mainly involves use of different preservation techniques ranging from dehydration to pickling. Variety of

Table 3
Novel techniques in onion processing and their impact on onion nutritional quality.

Sr. No.	Technique Used	Source Used or concentration	Storage Conditions	Findings	Impact on nutritional quality	References
1.	Artificial/Fast Curing	Ultrasonic Fogger	Temperature: 2°C Humidity: 70% Storage time: 10 months	Fast drying of green neck is observed after fast curing of onion bulb at 30°C and 98% RH Less weight loss during storage in comparison to non-fast cured bulb Reduction in microbial rot spoilage No early sprouting	• Quercetin levels increased from 2.97 to 3.05 g kg^{-1} during controlled the curing process • Reduction in tannic acid levels from 1.36 to 0.97 g kg^{-1} • No effect on lachrymatory factors levels during fast curing	Eshel et al., 2014 Naqash et al., 2022
2.	Ozone Gas Treatment	Surface dielectric barrier discharge electrode (SDBD) (1.27±0.024 ppm) Pulsed ozone treatment	Temperature: 2°C Humidity: 70% Storage time: 2 months	Reduce total count of bacteria and fungi by 4 log and 0.92 log (CFU/g) respectively Reduce rotting percentage and softening of bulbs compared to control Lesser impact on bulb colour - nonsignificant decrease in anthocyanin content	• Weight and soluble sugar content are not affected by ozone treatment • Pulsed dosage of ozone at 400 ppm levels enhanced phenolics and flavonoids content and antioxidant activity • Increase in ozone concentration decreased the pungency factors (pyruvic acid and ascorbic acid).	Lim et al., 2021 Shelake et al., 2022
3.	Hydrogen Peroxide (H_2O_2)	10%, 20%, 30%	Temperature: NM Humidity: NM Storage time: 12 months	Soaking of bulb in H_2O_2 solution resulted in a decreased timing of sprouting and rooting Soaking bulbs in 20% H_2O_2 solution for 2-4hrs was found to be effective in breaking endodormancy 30% solution reduce significant time of rooting in comparison to 10 and 20% solution	NM	D'Angelo & Goldman, 2019
4.	Sulphur fumigation	50g/m^3 (for 1 to 5 hours)	Temperature: NM Humidity: NM Storage time: NM	Reduced weight loss rotting and sprouting Reduced black mould infection	NM	Tripathi, & Lawande, 2019
5.	Thymol Fumigation	10 mg L^{-1} (weight: volume of the whole storage room	Temperature: 0-4°C Humidity: 70-80% Storage time: 10 months	Ffficient in inhibiting fungal pathogens when compared to conventional sulphur treatment Significantly reduced the lesion diameter on the onion bulbs	NM	Ji et al., 2018 Oh et al., 2022
6.	Microwave hydro-diffusion gravity technique	Microwave hydro-diffusion gravity technique	Temperature: NM Humidity: NM Storage time: NM	A combination of 400 W and 14 min was found to be the best for dehydration of onion slices Better texture, and colour compared to hot air drying	Enhanced colour and sensory property	Khan et al., 2016
7.	Non-thermal Plasma Fumigation/ Cold Plasma	480 s treatment of onion seeds Onion flakes were treated with moisture vaporization-combined helium dielectric barrier discharge-cold plasma (CP) @ voltage, frequency, and time 9 kV, 15 kHz, and 20 min respectively Onion powder treated with High microwave cold plasma at 400. 474, 650, 826, 900 W for 10-40 min	Temperature: NM Humidity: NM Storage time: NM	Cold plasma treatment of onion seeds resulted in reduction of microbial contamination Decontamination of value-added products such as onion powder and flakes. Cold plasma treatment was found effective against microorganisms which are resistant to chlorine disinfectants	There were no significant changes in the ascorbic acid and quercetin content and antioxidant property capacity of the onion flakes and powder when compared with the untreated samples	Mandal et al., 2018; Kopacki et al., 2017; Kim et al., 2017; 2018
8.	Gamma irradiation	^{60}Co (0.01-0.2kGy) 1 kGy gamma irradiation with 0.1% sodium benzoate treatment for green cut onions	Temperature: 24-34°C Humidity: 40-75% Storage time: 10-12 months	Physiological weight loss, rotting and sprouting is less in irradiated (0.01-0.2 kGy) onion bulb. Onion bulbs irradiated at 0.15 kGy minimize physiological weight loss (3.25%), low microbial load i.e., viable bacterial count and sprouting upto 21 days compared to controlled onion bulb without altering nutritional quality Exposure to gamma rays reduced the TSS loss by up to 30% during 4-6 months storage	Dose of 0.2 kGy showed no damage to the onions and good retention of niacin (Vitamin B3), pyridoxine (Vitamin B6) and Vitamin C Increased chlorophyll and Carotenoids in green cut onions	Abdullah et al., 2018; Sharma et al., 2020; Memon et al., 2020; Firouzi et al., 2021; Kiran et al., 2024

NM- Not Mentioned 8.7 Economics of novel techniques in Onion processing products have been generated from fresh onion bulbs and are used as food and flavour ingredient. These include, dehydrated onion (flakes or powder), ready to use onion paste, onion juice, onion essential oil as flavouring agent and ready to use fresh cut onions (Bahram-Parvar & Lim, 2018). A brief process flow involved in production of various value-added products of onion are presented in Fig. 4.

9.1. Dehydrated Onion (Flakes and Powder)

Dehydration is the most commonly practiced and less-expensive preservation technique in onion value addition (Süfer et al., 2017). Dried onions have great commercial significance in world trade and are available in several forms such as flakes, minces, chops and powder. Dehydrated onions are used as flavour additive in variety of food formulations such as soups, sauces, and products (Sahoo et al., 2015; Grewal et al., 2015). The average moisture content in onions range between 84% and 90% on weight basis and they are brought to less than 7% through different techniques such as convective, fluidized-bed, microwave, and infra-red drying. Traditionally, onions are preserved in the form of onion flakes through sun drying (Mitra et al., 2012). The factors that affect the drying process are total solids content, particularly insoluble solid content and ratio of reducing to non-reducing sugar. Onion varieties with TSS content between 15% and 20% and high pungency are recommended for dehydration purpose (https://horticulture.oregonstate.edu/oregon-vegetables/onions-dehydration-0).
Further the ratio of reducing to non-reducing sugar content should be lower to reduce the discoloration and browning during dehydration (Lewicki et al., 1998). Among the various dehydration techniques, convective drying is most commonly utilized in the industry. Onions are dried as thin slices and the optimum temperature employed for dehydration are between 50°C and 80°C and air velocities ranging between 0.6 to 1.5 m/s (Kaymak-Ertekin and Gedik, 2005). Optimum temperature for dehydration was found to be 50°C, however stage wise dehydration at different temperatures has also been recommended for onion dehydration. However, constant exposure to heat results in loss of nutrients such as vitamin C, sugars and thiosulphinate concentration (Mota et al., 2010). Fluidized bed drying has been found to be effective in dehydration of onion slices and the acceptable air temperature less than 53°C resulted in best quality (Swasdisevi et al., 1999). In addition to these, infrared and microwave drying have been found to be effective in dehydration of onion slices. In case of infrared drying, the drying rate was directly proportional with infrared power at any given air temperature and velocity (Sharma et al., 2005). Microwave drying of onion slices were found to be effective in retaining the colour and phenolics content of onion along with shorter drying time when compared to convective drying (Arslan and Özcan, 2010). Use of low microwave power with hot air decreases the average temperature required for drying reducing the chance of overheating. Microwave-hot-air drying combination at 50-60°C with 100-150 W microwave power yielded best results during onion dehydration (Maftoonazad et al., 2022). However, microwave-based dehydration caused more shrinkage (Mitra et al., 2012). Vacuum and freeze drying have been tested for commercial production of dehydrated onion products among others. Freeze dried onion products had better rehydration capacity, showed least shrinkage and possessed better sensory properties in terms of colour, aroma when compared to other forms of drying (Freeman and Whenham, 1974). However, the higher operational capital and operational expenditure in maintaining the temperatures and freezing has resulted in their limited use commercially. Osmotic drying of onion slices has been tried and pretreatment with 20% salt solution at room temperature for 1 h resulted in better solid yields after the dehydrated products (Sutar and Gupta, 2007).

9.2. Ready to eat (RTE) Onion

Onions are a key ingredient in many cuisines and processed products, leading to a high demand for them. Additionally, the market for ready-to-eat (RTE) food products has been growing due to the changes in consumption patterns and increased convenience (Teshika et al., 2019). Processing onions not only adds value to the product and offers variety

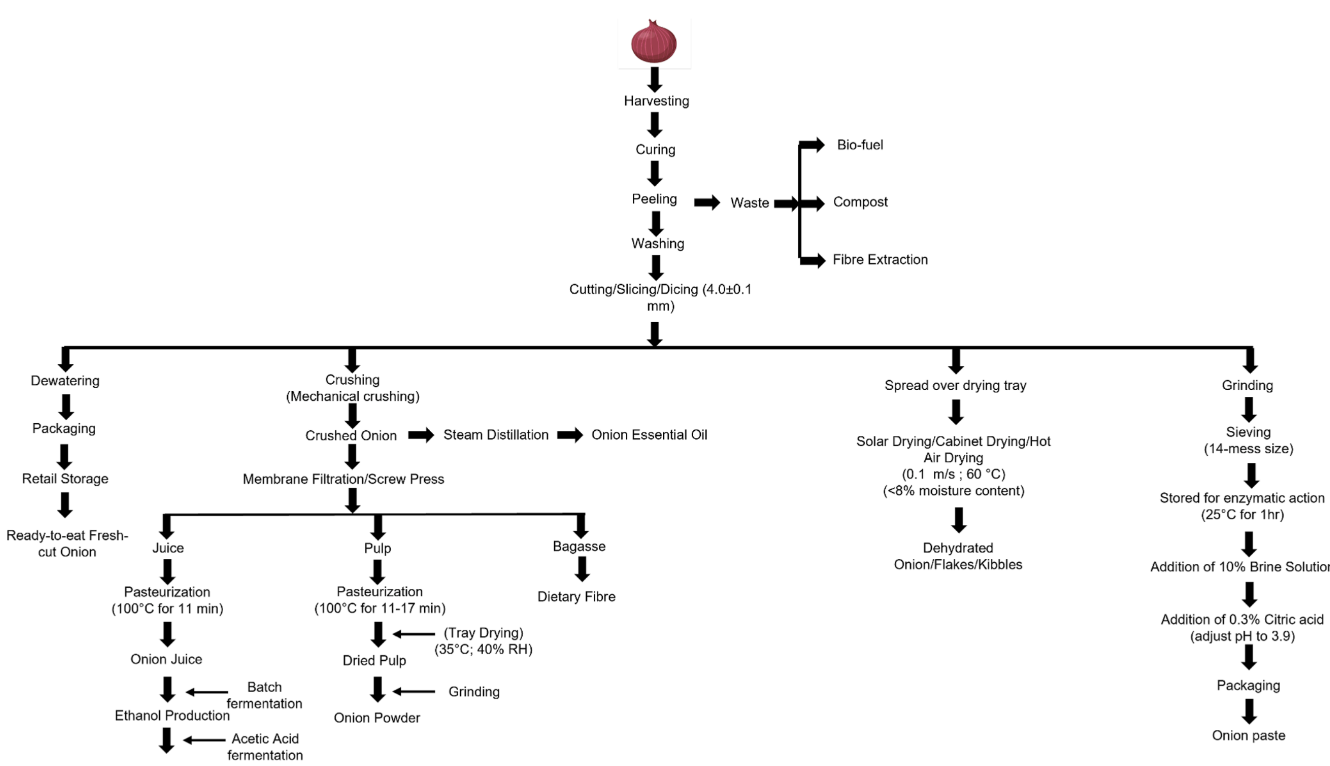


Fig. 4. Value added products of onion.

but also reduces wastage and in-store labor. Currently, various vegetables are available as fresh cuts to save time for end-use consumers. However, fresh processing of onions leads to the release of lachrymatory compounds and odours that cause irritation to the lacrimal glands and are unpleasant for many consumers. As a result, the demand for fresh-cut, ready-to-eat onions has significantly increased.

The production process of RTE fresh-cut onions involves various unit operations such as sorting, washing, peeling, slicing, dewatering, and packaging. The goal of these unit operations is to ensure the delivery of safe and nutritious produce. Dewatering of fresh-cut onions is achieved by centrifugation at moderate speed and time to prevent tissue damage and minimize the risk of leakage post-packaging. Proper packaging is essential to preserve the nutritional value and quality of the perishable fresh-cut onions, as cutting opens up cellular spaces for respiration. Modified or active packaging with O_2-absorbing sachets can extend the shelf life by reducing the respiration rate, which is influenced by storage temperature and gas exchange. Storage of fresh cut onions under modified atmospheric conditions containing 2% O_2 and 10% CO_2 controlled the respiration rate at 5 mg O_2 kg^{-1} h^{-1} throughout the storage, three times lower when compared to storage at ambient conditions (Bahram-Parvar & Lim, 2018). Thus, modulation of O_2 and CO_2 levels play a significant role in the storage of fresh-cut onions.

9.3. Onion paste/pulp

Onion is a key ingredient in culinary cuisine due to its distinct flavor. Onion paste is a valuable product that retains the real color and fresh flavor of onions. The quality of onion paste is influenced by factors such as total soluble solids, temperature, and particle size of ingredients. To prepare onion paste, onions are converted into puree using a grinder and passed through a mesh size 14 sieve for uniformity. The puree is then left at room temperature (25°C) for 1 hour in a covered container to allow enzymatic action for color and flavor development (Majid et al., 2021). To enhance the paste, NaCl (10% w/w) and citric acid (0.3% w/w) are added. NaCl increases total soluble solids, while citric acid acts as an antioxidant. Heat treatment of onion paste follows a first-order reaction pattern, where color degradation occurs with increasing temperature (Ahmed & Shivhare, 2001). Pasteurizing the onion pulp at 100°C for 11-17 minutes in a conventional autoclave, followed by storage at refrigerated conditions (5°C), can extend the shelf life of the product (Roldán et al., 2008). Majid et al. (2021) observed that sprouted onion pastes were able to retain the quality characteristics with lesser colour change, higher phenolics and flavonoids content compared to raw onion paste. The authors reported that the onion paste could demonstrate gelling properties useful for food processing applications. This process offers a potential use for valorisation of sprouted onion bulbs reducing the wastage of onion produce.

The onion pulp is utilized according to its use, either as is in product development or converted into powder. Onion powder also has a wide application and demand. It is prepared by hot air drying or convective tray drying. Conventional process involves mechanical dewatering of the paste followed by dehydration using a hot air dryer at 70°C, or in a convective tray drier at 35°C with 40% RH at a load of 4 kg m^2. The final product has less than 7% moisture content. The dried paste is then converted into fine powder using a mechanical grinder (Grewal et al., 2015).

9.4. Onion Juice

Onion juice is a valuable by-product that is obtained by dicing onions and converting them into a paste through mechanical crushing. The paste is then processed through a screw press or membrane filters to extract the juice. To stabilize onion juice, it is packed in sterilizable bags such as polyethylene terephthalate (PET) and pasteurized at 100°C for 11-17 minutes in a conventional autoclave. Pasteurization helps in maintaining the stability and preserving the prebiotic health benefits of onion juice (Benítez et al., 2013). Another method of processing onion juice involves using heat to produce a low-flavored product. In this method, macerated onions are flash-heated at 140-160°C, immediately cooled to 40°C, and then evaporated to achieve a 75% solid content, which increases the shelf-life of the juice. However, heating can lead to the loss of volatile aromatic compounds, resulting in a final product with a milder flavor profile (Lawande, 2012).

Pulping of onion generates three fractions namely paste (mixture of solid and liquid fraction), juice (clarified liquid portion) and bagasse (residual solid fraction). The total phenolics and flavonoid contents were highest in bagasse compared to pulp or juice. Roldan et al. (2008) evaluated the impact of different thermal treatments on the total phenolics, quercetin and antioxidant potential of paste, juice and bagasse in Spanish onion varieties. Among the three fractions, onion paste and bagasse contained multi-fold higher quercetin and total phenolics compared to the clarified juice. The authors attributed higher quercetin and phenolic contents in paste and bagasse owing to the localization of these phytochemicals in high concentration in the onion cell walls compared to the clarified juice which do not contain the cell walls. Thermal treatments such as pasteurization (100°C, 11-17 min) and sterilization (115°C, 17-31 min) resulted in 10-20 folds loss in polyphenols, specifically quercetin. Despite containing relatively lower levels of quercetin, onion juice also showed 3-6 folds loss from 214 mg 100 g^{-1} d.w. to 31 - 79 mg 100 g^{-1} d.w. after thermal treatments. However, the total quercetin content (721-724 mg 100 g^{-1} d.w.) in paste and bagasse were statistically similar after thermal treatments. Comparison of antioxidant activity as measured by percentage free radical scavenging revealed that onion paste contained higher radical scavenging efficiency compared to juice and bagasse under frozen conditions. However, thermally treated paste and bagasse showed similar free radical scavenging efficiency compared to juice. The study by Roldan et al. (2008) revealed that onion juice is more susceptible to thermal treatment compared to paste. Further they reported that order of phytochemical retention was highest in frozen products followed by pasteurized and least in sterilized products. Alternatively, the group proposed, low temperature (5°C) and high pressure (400 MPa) processing for pulping and juicing applications (Roldan et al., 2009). The authors observed that high pressure treatment under cold conditions enhanced the extractability of quercetin and retained the antioxidant capacity of onion paste at par with control samples.

9.5. Onion essential oil

Onions could be exploited for the production of distinct aroma and flavour owing to the presence of sulphur compounds in volatile form. Steam distillation is used for extraction of essential oils from onions, which mainly contains alkyl sulphides mainly methyl 5-methylfuryl sulphide, methyl 3,4-dimethyl-2-thienyl disulphide and 1-propenyl propyl disulphide. Onion oil is commonly used as a flavoring agent in various food preparations such as soups, salad dressings, and table sauces. Further, onion essential oil has been reported to possess strong antimicrobial properties, both bactericidal and fungicidal activity against several microorganisms such as *E. coli, Bacillus subtilis, Staphylococcus aureus, Aspergillus niger, Aspergillus terreus, Monascus purpureus, S. cerevisiae* with minimum inhibitory concentrations ranging from 0.18 to 1.80 mg ml^{-1}. Furthermore, they possess strong antioxidant (free radical scavenging and reducing power) properties in addition to their use as flavouring agent (Ye et al., 2013; Vazquez-Armenta et al., 2016). Additionally, onion essential oils have been reported to inhibit browning of cut vegetables, particularly potatoes by inhibiting the polyphenol oxidase enzyme (Vazquez- Armenta et al., 2014).

9.6. Onion Pickling

Pickling is a well-known method of preserving food that involves the use of brining, a high concentration salt solution (Behera et al., 2020).

Onion pickle is made by fermenting onion bulbs in a 10% brine solution for 3-4 days. During the fermentation process, sugars are converted into lactic acid, acetic acid, and alcohols. The finished pickle is then bottled in dark vinegar with caramel and pasteurized at 80°C (Lawande, 2012). Pickling leads to metabolic changes that result in unique organoleptic characteristics and extend the shelf life of the food. To make onion pickle, onions are cleaned, sorted, and blanched at 90°C for 5 minutes. The blanched onions are then packed in an airtight container with a 5% acidified brine solution prepared with a 15% NaCl concentration. The pickle is stored for four weeks (Mota et al., 2010).

9.7. Impact of processing techniques on nutritional quality of Onion

Thermal treatment such as dehydration is the most commonly practiced value-addition process in onions. Oven drying of onion slices between 80 and 120°C increases the phenolic content and antioxidant activity while reducing the sugar content. However, increasing temperatures >120°C resulted in degradation of phenolic acids and antioxidant activity (Sharma et al., 2015). Naqash et al. (2021a) evaluated thermal treatments on onion paste ranging from of 70-90°C at different time intervals ranging from 5 to 22 mins. The most optimum temperature-time ratio for minimal nutritional loss was at 87°C for 15 mins where retention of quercetin, pyruvic acid and colour levels were observed. In case of freezing treatments, Lee et al. (2008) and Pérez-Gregorio et al (2011) observed a reduction in flavonoid and anthocyanin content during freezing of onion bulbs in carbon dioxide snow for 3 mins. However, upon freeze drying under 4.2 Pa of vacuum pressure at -70°C for 24 hours the flavonoids and anthocyanins contents were enhanced. High pressure processing of onion bulbs in a hydrostatic pressure unit at pressure ranging from 100-400 MPa and temperature between 0 and 50°C was studied by Roldán-Marín et al., (2009). The authors observed that low temperature (5°C) treatment between 100 – 400 MPa pressure significantly increased the extractability of quercetins (total flavonol) and total phenols while treatment at low and medium temperatures (5°C and 27.5°C) at high pressure of 400MPa maintained the total phenolics content and increased the antioxidant capacity. Exposure of onions to fluorescence light in an irradiation chamber at 25°C at two different photoperiods *viz.*, 24 and 72 h resulted in an enhancement of flavonoid content by 6.5%-75.19% (Roldán-Marín et al., 2008; Karpagam et al., 2021). Owing to its high culinary value, onions are cooked by variety of methods such as frying, sautéing, boiling, steaming, microwaving, and baking. Cooking resulted in loss of flavonoids with maximum loss occurring with frying (33%) followed by sautéing (21%), boiling (14-20%), steaming 14%, and least in cooking microwave cooking (4%) (Lee et al. 2008; Roldán-Marín et al., 2008).

10. Global Onion standards

The quality standards for onions that are cultivated from the *Allium cepa* L. Group and marketed to customers in their natural condition are laid forth in the United Nations Economic Commission for Europe (UNECE). The basic specifications, categorization, dimensions, tolerances, presentation, and labelling of onions are all covered in the paper. The agreement intends to encourage high-quality production, ease international commerce, and safeguard consumer interests. According to the UNECE standard, the onion can be divided into two groups, class I and class II. Class I onions must be of a high standard and a distinctive variety. The bulbs must be solid, compact, and devoid of root tufts; however, minor form and colouration flaws are acceptable as long as they don't detract from the onion's overall quality. Class I onions may contain up to 10% by weight or quantity of onions that do not fulfil the standards for the class but do so for Class II. Class II onions must have moderately firm bulbs; small form and colour flaws, minimal bruising, root tufts, and skin fractures are permitted as long as the onion flesh is unharmed. The size tolerances for both classes are 10% of onions that do not meet the standards for sizing, whether measured in terms of quantity or weight. The UNECE standard based grading does not have any specific size or weight requirements. However, in India the onion bulbs are classified into three grades, *viz.*, A, B and C based on the size of the bulbs. The grade A onions have bulb size > 80 mm while grade B have sizes ranging from 50-80 mm and grade C have a size of 30-50 mm. (www.dogr.icar.gov.in). In addition to size and soundness of the bulbs, the packing must clearly describe the variety of onions in terms of onion presentation. The visible portion of the package's contents must accurately reflect everything within. To adequately safeguard the crop, onions must be packaged. To prevent any damage, the materials utilised within the packaging must be pristine and robust. Non-toxic ink and adhesive should be used for the printing and labelling and all foreign material must be removed from packages. (UNECE standard FFV-25, 2019).

11. Valorisation of onion process residues

Onion processing is a common activity in both domestic and industrial settings. However, it also generates a huge quantity of waste materials, such as the tops and bottoms of the bulbs, the outer peels and skins, and the two outer layers of the flesh. It is estimated that 90 to 150 tonnes of onion wastes are generated per year during post-harvest processing (harvesting, sorting, curing, packaging and storing) in India (Salunkhe et al., 2022). These onion wastes are often discarded or composted, despite having valuable properties and potential applications. Črnivec et al. (2021) reported that the approximate cost of disposal of above-mentioned onion wastes and residues are estimated up to 40 Euros per ton. Thus, it becomes important to valorize the onion wastes for enhanced resource recovery and economic viability.

One of the main cornerstones of sustainable development is the use of onion waste. Adopting a method that prevents the development of trash satisfies the demands of both the present and future generations. Phenols, flavonoids, and flavanols, which have antioxidant, anti-inflammatory, and antibacterial properties, are abundant in onion wastes (Kumar et al., 2022). Through several inventive methods, including solvent extraction, microwave-aided extraction, ultrasound-assisted extractions, and deep eutectic solvent extraction that is also environmentally benign, these bioactive chemicals may be isolated from onion waste. The development of nutraceuticals can employ extracted alkyl cysteine sulfoxides, aglycones, and glycosylated derivatives of quercetin, among other compounds. Additionally, abundant in polysaccharides, onion wastes can be used to create enzyme immobilisation carriers. After treatment, brown onion peel wastes may be converted into cellulose and hemicellulose-based carriers. About 60% of the dry matter in brown onion skin is insoluble fibre, mostly polysaccharides. As a growing medium, onion waste extract has also been used to increase the biomass of microalgae that may then be used in the manufacture of biodiesel, onion peel wastes can be employed as a growth medium (Karpagam et al., 2021). In addition to these, a variety of mono-, di- and polysaccharides, including xylose, arabinose, rhamnose, mannose, galactose, glucose, and uronic acids, may be recovered from onion waste (Cho et al., 2021). Onion waste can also be converted to valuable bio sugar through different strategies like batch column and continuous column systems which can be an alternative feed source for honey bees (Cho et al., 2021). Onion peel extracts can also be used as anti-browning agents in minimally processed vegetables. The onion extracts inhibit polyphenol oxidase (PPO), which is mainly responsible for browning and it can be a cheap and green method to prevent the browning of vegetables (Tinello et al., 2020). Recently Abinaya et al. (2023) showed that excess red onions can be converted into red onion gummy jelly which is rich in antioxidants and can be a better alternative to other jellies currently present in the market.

Fermentation of onion waste is another popular technique. Acetic acid and ethanol can be produced by fermenting the onion waste. Simultaneous saccharification and two-step fermentation (SSTF) and saccharification and co-fermentation (SSCF) have been used to create acetic acid from dried onion waste. The SSTF technique involved treating dried onion waste with pectinase and cellulase to produce bio-sugar, which was then inoculated with *Saccharomyces cerevisiae* to produce bio-ethanol. The bio-ethanol was then combined with *Acetobacter acetii* to create acetic acid. In the SSCF method, acetic acid was produced directly by fermenting onion waste (Kim et al., 2020; Sagar et al., 2022). Other processing techniques that help produce value-added products like levulinic acid, hydrogen, methane, lactic acid, propionic acid, ethanol, inulase, biogas, and fumaric acid can be used to valorise onion waste include thermochemical, physical-chemical, and biochemical conversion pathways (Vigneshwar et al., 2022). The onion waste was hydrolyzed using enzymes such as cellulase, pectinase, and xylanase to produce glucose, which may be utilised to make bioethanol (Choi et al., 2015). According to previous literature, onion waste is a promising substrate for hydrolysis-produced organic acids and biofuels. Waste from the processing of onions is also used as sorption material to remove different contaminants (metal ions, dyes, and antibiotics) from aqueous environments, thus it can be used as water-purifying material (Shaikhiev et al., 2022). When onion trash can also be vermi-composted along with other materials, an organic amendment suitable for use in agriculture can be produced. The finished vermicompost is a developed product with excellent organic and nutritional content (Pellejero et al., 2020). The waste from onions may be treated to produce colours like anthocyanic colours and fructooligosaccharides. Onion peel is one of the most important dietary sources of anthocyanin flavonoids, which give onions their red and purple colour (Beatrice, 2017). Furthermore, onion wastes may be utilised to create natural pigments and dyes, which have a lower environmental effect and better thermal stability than synthetic colours (Nguyen & Bechtold, 2021). Natural food colourants derived from onion wastes like anthocyanins were used to produce red yoghurt (Mourtzinos et al., 2018). Bioprocessing of onion waste into value-added products is presented in Fig.5

12. Futuristic technologies for reducing post-harvest losses of onions

With the advent of smart agriculture technologies such as artificial intelligence (AI) and internet of things (IoT), the quality of agri-horti produce can be ascertained on real time basis towards effective post-harvest management (Dhanaraju et al., 2022; Kutyauripo et al., 2023) The most common principle used in the smart technologies are disorder inspection through two dimensional and three-dimensional imaging of the produce followed by image analysis and classification by AI tools (Tempelaere,et al., 2023). Use of classical red, green and blue wavelength capturing cameras (RGB) and camera's sensitive to UV, near infra-red regions allow detection of quality parameters that are invisible to human eyes. In addition, use of X-rays, computed tomography (CT) scan, magnetic resonance imaging (MRI) and thermal imaging can be exploited for obtaining 3D images and volumetric imaging of the produce (Mahanti et al., 2022), especially for fruits and vegetables such as apple (Shahin et al., 2002), pear (Yu et al., 2022), apricot (Karmoker et al., 2018), and seeds (Van De Looverbosch et al., 2022). These technologies are non-invasive and offer a high throughput during the quality assessment and improved decision making. In addition, most of the fruits and vegetables carry a unique aroma profile due to the presence of volatile organic compounds (VOCs) which can be exploited for real time monitoring of the crops. This branch of study that focuses on identifying, characterizing and measuring the volatile compounds originating either due to metabolic processes or microbial contamination is known as volatilomics (Lytou et al., 2019). This technique can be used for ensuring food safety, quality and authenticity (Mengers et al., 2022). Considering the significant production and enormous post-harvest losses of onions coupled with a year-round demand and supply necessitates integration of aforesaid real time quality control technologies.

12.1. *Applications of image processing techniques on onion quality control*

Application of image processing in post-harvest management of onions has been practiced in recent years. As discussed earlier, rotting and sprouting are visually evident and major post-harvest losses that impact onion. Non-invasive technologies such as infrared hyperspectral imaging and shortwave infra-red imaging have been widely used for quality assessment of onions during storage. The IR based spectroscopy and scanning was more appropriate for onion quality measurement as the technique is more suitable for the analysis of products high in water and carbohydrate content (Islam et al., 2019). For example, sour skin disease in onions caused by *Burkholderia cepacia* causes huge economic losses for farmers. A shortwave hyperspectral imaging was deployed for detection of the sour skin in onions (Wang et al., 2012). The process involved capturing of hyperspectral reflectance images between 950 mm and 1650 nm and use of image analysis software for detection of infected onions. A characteristic spectrum at two wavelengths, *viz.*, 1070 nm and 1400 nm were observed in the neck region of infected onions (Wang et al., 2012). The authors classified the images based on pixel number followed by Fiser's discriminant analysis to identify infected and non-infected onions. Additionally, other image processing parameters such as max, contrast and surface homogeneity were deployed for identification of the infected onions. The image processing approach resulted in 87% accuracy in differentiating the healthy and sour-skin infected onions. In another example, Wang et al. (2013) deployed a line-scan hyperspectral imaging in the spectral region between 400 nm and 1000 nm for detection of total soluble solids (TSS) and dry matter. Three sensing modes were employed for detection namely, reflectance,

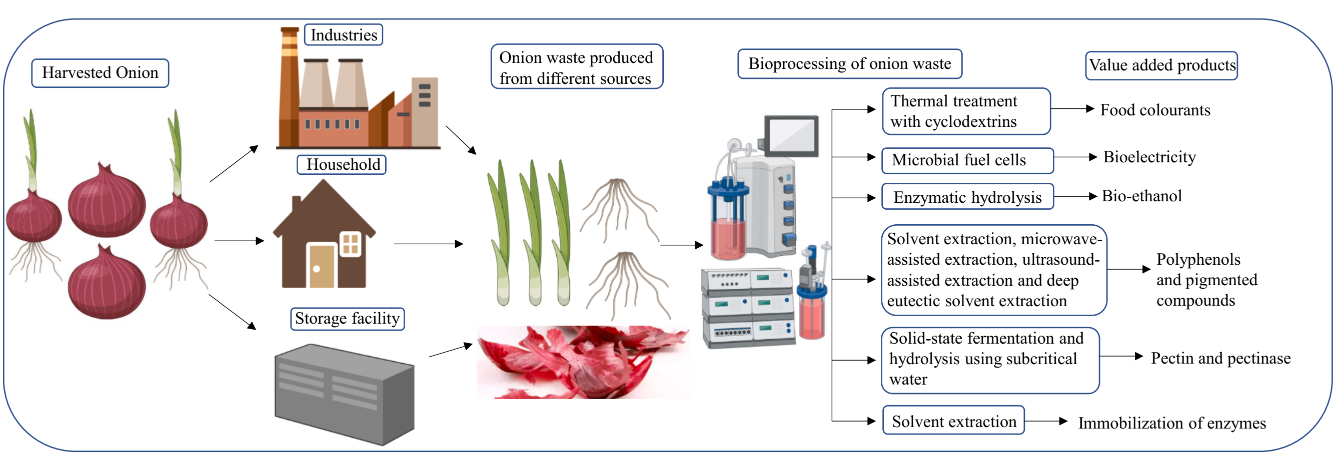


Fig. 5. Bioprocessing of onion waste into value-added products through various strategies (Fig.s taken from Biorender.com).

interactance and transmittance. The authors reported that use of interactance mode resulted in better results compared to reflectance or transmittance. A high positive correlation ($r^2 = 0.93$; r = coefficient of determination) with a standard error of 1.6% was achieved with respect to determination of dry matter content of onions (Wang et al., 2013). Shahin et al. (2002) employed x-ray imaging followed by image processing using neural network for the determination of internal defects in onions. Spatial and transform features were applied for classification of onions. Using the neural network approach, the authors reported an accuracy of 90% with losses and false positives at 6% and 10% respectively. However, the accuracy of spectral measurement is significantly affected by positioning of the bulb against the sensor setup. In an experimental study to determine internal rot in onions using visible and near infrared transmittance spectroscopy, Kuroki et al., (2017) reported that the basal plate of the onion bulb had remarkable scattering properties and interfered with spectral acquisition of the internal scales. Absorbance at 736 nm was identified to be ideal for detection of rot in scales and positioning angles of bulb against the sensors determined the efficiency of imaging. A dual beam spectral measurement for detection of internal rot in onions have been found to be more efficient compared to single beam measurement in the visible and near infrared transmittance spectroscopy (Nishino et al., 2019). In this technique, the onion is placed with its neck facing upwards and one beam passing through the neck and the other across the equator of the bulb. The technique was very effective in detecting mildly rotten onions which escaped during the application of single beam transmittance spectroscopy. Further the technique was effective in segregating rotten onions with minimal misidentification and an accuracy of 98.5%. These techniques were sensitive and more suitable for segregation applications at the gate, before reaching the consumer. Similarly, spatially resolved transmittance spectroscopy technique at two different wavelengths viz., 728 nm and 805 nm were deployed for the determination of internal rots in onions and was found to be effective in determining rottenness (Sun et al., 2020). Imaging techniques such as hyperspectral scanning, near infrared transmittance spectroscopy are more useful in disease diagnosis and prevalence during storage of bulbs. Islam et al. (2019) compared different techniques such as near IR spectroscopy, multispectral scanning, hyperspectral imaging in the visible and NIR regions and spectral imaging at the short-wave infrared (SWIR) for detection of spoilage in cold stored onion bulbs. The authors observed that SWIR could be effectively used for segregating healthy and infected bulbs.

12.2. Volatilomics

Onion has a unique aroma and pungent flavour which differentiates it with other root crops owing to the presence of VOCs particularly, organosulphur compounds (OSCs). Zhao et al. (2021) identified fifty-three different VOCs including alcohols, esters, furans, ketones, carboxylic acids, and sulphur compounds and reported that dipropyl disulphide and other sulphide compounds were characteristic to onion. The volatile nature of the OSCs can be exploited for determination of the quality and authentication of onion varieties. The branch of metabolomics that focuses on identifying, characterizing, and measuring every volatile metabolite present in a biological system is called volatilomics. These volatile organic compounds (VOCs) are referred to as "volatilomes" (Mengers et al., 2022). A typical volatilomic approach for quality control and post-harvest management of onions can be achieved through solid phase micro-extraction (SPME) coupled with headspace gas chromatography–mass spectrometry (GC–MS) technique (Wang et al., 2019). Fernandes et al. (2020) determined the volatile signatures of onions obtained from different geographical regions and reported that significant variations were observed between the varieties. The authors identified VOCs such as dipropyl disulphide, 3-(Acetylthio)-2-methylfuran, dimethylmethoxyfuranone, ethylfuranone, acetyloxy-dimethylfuranone and lactones as potential chemical markers for differentiating onions from different geographical regions. Similarly, Cozzolino et al. (2021) identified 2-methylfuran, as potential differentiating marker for classification of onions from different geographies. It has been reported by several authors that the volatile profiles of onions vary during storage and the signatures significantly vary between healthy and infected/rotten onions (Kleman, 2023; Vikram & Kushalappa, 2005; Wang et al., 2015, Labanska et al., 2022). Wang et al. (2019) demonstrated that healthy and microbe-infested onion bulbs showed completely different volatile profiles. The authors identified twenty-nine compounds and the prevalent VOCs released from healthy bulbs were hexanal, acetone, and dimethyl disulphide. During the microbial contamination, the concentration of the aforesaid VOCs significantly reduced and following compounds was identified namely, propene, carbon disulphide, isoprene, pentane, 2-methylfuran, 3-methylfuran, 1-propenethiol, hexane, and methyl propyl sulphide using headspace gas-chromatography mass spectrometry (GC-MS) technique. In the case of soft rot and *Penicillium* infected onions, the concentrations of ethanol, 1-propanol, 1-propanethiol, acetic acid and methyl propyl disulphide were higher compared to healthy bulbs as determined using SPME coupled with GC-MS. Particularly, 3-methyl-1-butanol was specific to soft rot and styrene in the case *of Penicillium* infected onions (Wang et al., 2015). With the advancement of technologies, non-destructive approaches for determination of volatiles have been employed recently. One such device used for electronic sensing of aroma is called electronic nose (E-nose). In several industries, including agriculture and the food processing sector, the use of E-nose is becoming more common (Ghosh et al., 2022). E-nose consists an array of gas sensors for the detection of volatile profiles of crops, including onion. One of the key application domains where e-Nose has been utilized is for testing and quick sensory quality assessment of food and beverage. E-nose based quality evaluation offers faster, accurate, repeatable data free from human biases, subjectivity, and inaccuracy. After being trained with a sufficient amount of labelled data and an appropriate machine learning model, E-nose can reasonably predict the quality of the sample being tested in several specified classes. E-Nose was used for the detection of early spoilage in onions during post-harvest storage by Ghosh et al. (2022). Li et al. (2011) observed that microbial infected onions produced two-fold higher VOCs compared to healthy bulbs through an experimental validation by infecting the bulbs with *Botrytis allii* and *Burkholderia cepacia* that causes neck rot and sour skin. Bulbs infected with neck rot produced unique volatile molecules such as Z-propanethiol-S-oxide and (Z)-1-(methylthiol)-1-propene while bulbs with sour skin produced unique VOCs such as 2-nonanone and 2-octyl-5-methyl-3 (2H)-furanone as detected through headspace GC-MS analysis. The GC-MS results validated the differences observed in the volatile signatures observed between healthy and infected onion bulbs through E-nose technique. This was further corroborated by Konduru et al. (2015) through deployment of E-nose for determining the VOCs signatures between healthy and infected onions. In another recent example, onion basal rot caused due to the *Fusarium oxysporum* infection was identified using E-nose with an accuracy up to 96.9% (Labanska et al., 2022). E-nose based VOCs profiling offers a non-destructive option for quality control during onion storage. However, a more detailed study of volatilomics in onions under different storage conditions could provide more valuable insights into their quality and flavour. Volatilomics can be exploited for determining the progression of disease and can be integrated with real time monitoring systems for effective post-harvest management.

12.3. Flavoromics

Flavoromics is developed from the domains of chemometrics and metabolomics, and it is essentially a non-targeted way of rapidly collecting massive amounts of data on a broad sample set and then mining the data to comprehend complicated problems. Data streams can be generated by volatile or non-volatile analysis, NMR, sensory data, or manufacturing standards. The field of flavoromics has emerged lately as a means of employing data driven and non-reductionist processes to investigate the molecular underpinnings of flavour (taste and fragrance) (Pérez-Jiménez et al., 2021). It is derived from the fields of chemometrics and a wide range of analytical techniques to provide data on a diverse sample set to understand complex problems related to flavour formation in foods. There is ample evidence in recent literature to support the wide range of uses of flavoromics in food and beverage research. By using flavoromics techniques, one might gain a deeper comprehension of food quality and flavour profiles (Ronningen & Peterson, 2015). By utilizing flavoromics, researchers may now look at a food's whole flavour attribution process as opposed to just concentrating on the pre-selected scent molecules of interest (Pérez-Jiménez et al., 2021). Previously, to understand flavour perception from a comprehensive perspective, a flavoromics approach was used to identify the key flavour compounds in citrus fruits like mandarins, oranges, and sweet-orange-like mandarin hybrids by Feng et al. (2021). Similar to this, 28 scents were filtered out as potential fragrance markers to differentiate the five malts in the aroma boundary compositions of barley malts. In all, 96 volatiles were discovered in all malts with HS−SPME− GC− MS (Gu et al., 2022). The flavoromics approach was also used to study wine flavour chemistry by Pérez-Jiménez et al. (2021) which helped to better understand the wine composition and other factors related to wine sensory properties. In the context of onions, specifically green onions, the flavour can be influenced by various factors. Aroma-active components of fried green onion were identified by Wang et al. (2023) wherein they identified flavour compounds furaneol, dimethyl trisulphide, and allyl methyl trisulphide were identified as the key aroma compounds. This technique could be extended to study the impact of different processing technologies on onion bulbs. Further, value addition of onions involves thermal treatments which could alter the flavour of the onion products and flavoromics could be employed for understanding the impact of these treatments on the aroma profile of onion products.

The use of advanced analytical techniques such as image processing, volatilomics, and flavoromics enables faster and more accurate identification of microbial infection and spoilage in onions during long-term storage. Integrating these methods with modern technologies like artificial intelligence (AI), Internet of Things (IoT), and cloud technology allows for real-time monitoring of onion quality. These techniques can also be applied in precision agriculture to enhance crop quality at the farm level. IoT utilizes humidity and temperature sensors to collect periodic temperature data. Machine learning algorithms are then trained using data from remote sensing. Online measurement of temperature and humidity as markers for quality changes during onion storage was demonstrated by Islam et al. (2019). Similarly, Ahmed et al. (2022) showed how monitoring onion production stored in warehouses can help reduce wastage. A typical E-nose based futuristic post-harvest quality management of onions is presented in Fig. 6.

13. Conclusion

Onion is a widely farmed vegetable in the *Allium* genus worldwide. At least 175 countries grow onions in the world and India is the top producer of onions producing about 26 % of the world's total onion production. However, onion post-harvest losses are estimated to range from 30 to 40%, mainly due to improper storage conditions, diseases, pests, and physiological disorders. Therefore, improving onion post-harvest storage is crucial for enhancing food security, reducing waste, and increasing farmers' income. In this review, we summarize the current knowledge on onion post-harvest physiology, storage methods, bacterial and fungal diseases and management quality parameters, and challenges. The novel techniques which are being used in the post-harvest management of onions and strategies for valorization of onion waste and converting them into high value products biorefinery approach is discussed. We also discussed the future perspectives in onion disease diagnosis during post-harvest storage, such as the use of image processing and volatilomics techniques. We conclude that onion post-harvest storage is a complex and dynamic process that requires multi-disciplinary and integrated approaches to optimize the quality and shelf life of this important crop. The present paper highlights effective pre- and postharvest strategies for reducing the postharvest losses of onions thereby addressing the grand onion challenge of India.

Web links cited

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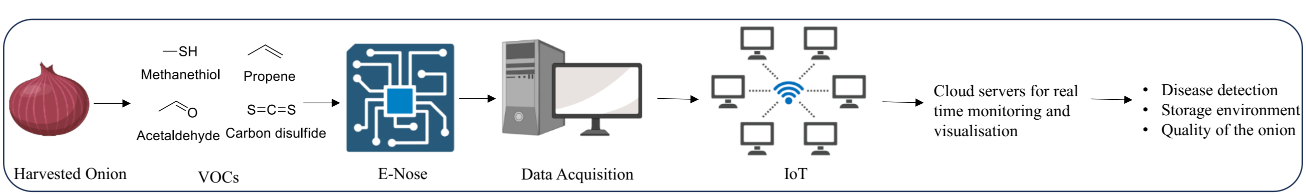

Fig. 6. E-nose based quality control for post-harvest management and onion storage (Fig.s taken from Biorender.com).

CRediT authorship contribution statement

Kalit Sharma: Writing – original draft, Methodology. **Manoj S Aroor:** Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Sampa Das:** Writing – original draft, Methodology. **Birinchi Bora:** Writing – original draft, Methodology. **Mahesh Gupta:** Writing – review & editing, Writing – original draft, Validation, Methodology, Funding acquisition, Data curation, Conceptualization. **Vidyashankar Srivatsan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

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Supplementary materials

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Data availability

No data was used for the research described in the article.

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