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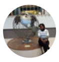
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Pre- and postharvest factors affecting quality and safety of Pepper (*Piper nigrum* L.)

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Abstract

The quality and safety of pepper (*Piper nigrum* L.) are a function of crop management practices, harvest maturity, harvesting methods and subsequent handling after harvest, including storage conditions and processing methods. The review shows that volatile oil decreases with shade intensity (15–30%). Essential oil, oleoresin, piperine and monoterpenes (thujene, α-pinene, sabinene, limonene, α-phellandrene and linalool) increase with altitude, while β-caryophyllene and total phenol decrease with increase in altitude. Fermentation of ripe pepper fruits forms odorants (butanoic acid, 3-methylindole, and 4-methylphenol) attributing intense faecal/shed-like off-flavour white pepper powder. Low-drying temperature (≤56°C) and duration (≤3 hrs) lead to low bulk density (0.17 g/ml) and low moisture loss (31%). Excessive soaking of black peppercorns prior to mechanical decortication reduces volatile oil and increases moisture content and broken berries. Availability of heavy metals in grinding machines increases the level of heavy metals; Fe (69.8–1147 mg/kg), Pb (21.3–947 μg/kg) and V (64.1–1072 μg/kg) in pepper powder. Storing peppercorns along with other materials enhances cross-contamination of heavy metals; Pb, Cd and Cr. High moisture content (>13%) and farmers' unawareness resulted in high (2200 to >30000 cfu/g) mycotoxins contamination. Environmental and industrial pollutants such as plasticizers, bisphenol A, polycyclic aromatic hydrocarbons and pesticides are also pepper contaminants of high merit. Radiofrequency pasteurization, vacuum-assisted steaming, ethylene oxide fumigation, atmospheric pressure plasma, dry heat sterilization, gamma-irradiation and ultraviolet-C light treatments are among strategies to enhance the quality and safety of pepper. More precautions also have to be taken to regulate the shade, drying temperature and duration, soaking duration, hygienic processing and storage in order to retain quality, minimize the risk of microbial or chemical contaminations and comply with standards.

Keywords: pepper, preharvest, harvesting, postharvest, quality, safety, standards

Review Methodology: The following databases were searched for relevant articles: CAB Abstracts, Web of Science Core Collection, PubMed, ScienceDirect, Scientific Electronic Library Online (SciELO), Semantic Scholar and Google Scholar. Keyword search terms used are the following: Pepper, *Piper nigrum*, crop management, postharvest treatment, microbial contamination, aflatoxins, heavy metals and quality standards. In addition, the references from the articles obtained by this method were used to check for additional relevant materials. Most recent publications (87%) that were covered in this review ranged from the year 2010 to 2021, while 13% ranged from the year 2002 to 2008.

Introduction

Pepper (*Piper nigrum* Linnaeus—Family Piperaceae) is one of the oldest, most treasured spices. Over many centuries, pepper has been an important part of commerce and has been a highly valued cash crop in many tropical countries [1]. Pepper has been nicknamed as 'Black Gold' and the 'King of Spices' because of its high volume in international spice market and consumption throughout the world [2]. Pepper fruits/berries, popularly called peppercorns, can be processed and presented into either green, black or white pepper products [3]. The prefix black, green and white is used to describe the appearance of pepper products, but 'black pepper' is popularly used to refer the crop plant, distinguishing from pepper of *Capsicum* spp. (i.e. chili). Pepper is utilized in foods and drinks as a spice or preservative, and as raw material in medical and food processing industries, owing to its peculiar pungent taste (flavour and aroma) and physiological actions. It has influenced the culture of citizens in various nations across the world, and has a remarkable history dating back to BC 1015–BC 66, the times of ancient civilization [4]. It plays an important role in the economy of producers [5, 6], exporters and importers in various countries worldwide [3, 4]. The total commercial production of pepper in the world (Fig. 1a) has been increasing at an estimated range of 510,184–732,524 Metric tons (MT) annually [7]. Vietnam with 102,570–262,658 MT year^{-1} stands out as the predominant producer and exporter of pepper, contributing over 30% of the world production [7]. Other major pepper producers include Brazil with 101,274 MT year^{-1}, Indonesia (88,715 MT year^{-1}), India (67,472 MT year^{-1}), Bulgaria (51,958 MT year^{-1}), Sri Lanka (48,253 MT year^{-1}), China (36,125 MT year^{-1}), Malaysia (30,457 MT year^{-1}), Mexico (9,141 MT year^{-1}) and Madagascar (5,542 MT year^{-1}). Asia stands out as the dominant producer of pepper, contributing 73.8% of the world production, followed by Americas (15.9%), Europe (7.1%) and Africa (3.2%) (Fig. 1b) [7].

Pepper is composed of essential nutritional components, which makes it a nutrient-rich commodity among spice crops [2]. Analysis of 100 g of pepper shows it contains calcium (0.4 g), phosphorus (160 mg), sodium (10 mg),

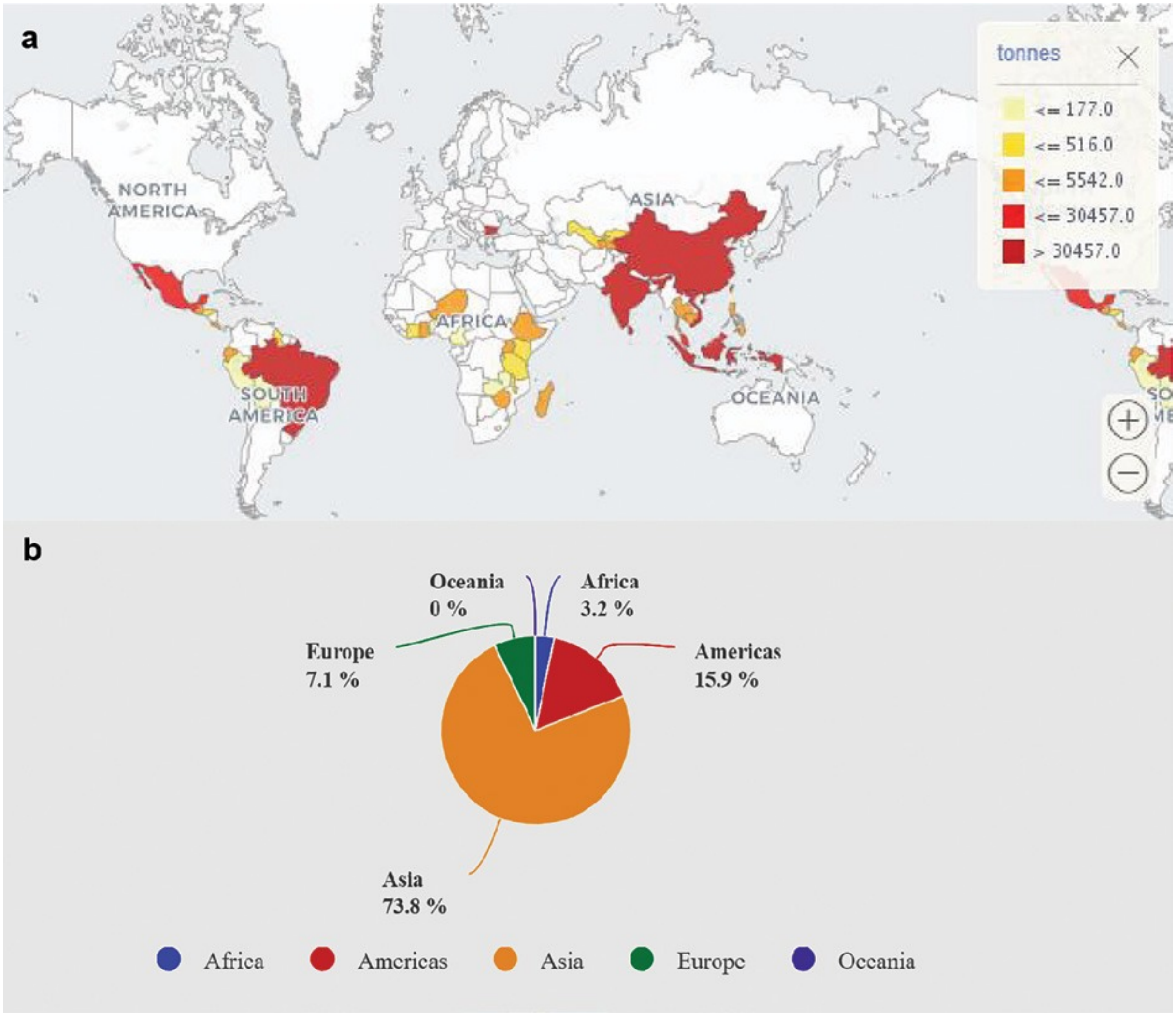

Figure 1. Production quantities and share of pepper by (a) country and (b) region.

potassium (1200 mg), iron (17 mg), thiamine (0.07 mg), riboflavin (0.210 mg), niacin (0.8 mg), vitamin A activity (19 IU), water (8 g), energy value (400 Kcal), protein (10 g), fat (10.2 g) and carbohydrates (66.5 g). The high elemental composition, particularly K, Ca, Mg, Na, Fe, Al and Se, qualifies pepper to be among the rich sources of essential mineral elements, while the low levels of heavy metals or toxic trace elements (i.e. Hg, Cr, As, C and Pb) minimize threat to human health via food chain [8]. Given the bioactivity of the crop [9, 10], pepper has been used in agricultural and pharmaceutical industries as a natural insecticide and antioxidant, respectively [11]. Pepper contains naturally occurring chemical components including amides/piperine [12], hence it is promoted as natural medicine against oxidative stress and inflammation associated with ischemic stroke (brain and cerebral ischemia) in humans [13–15]. Pepper is widely used in various herbal cough syrups [16], and it is also used in treatment of malaria [17, 18], cancer [19–21] and leukaemia [22]. Pepper inhibits pathogens causing food spoilage such as bacteria; *Escherichia coli*, *Bacillus cereus*, *Staphylococcus aureus* and *Klebsiella pneumoniae* [23, 24]. Pepper is proven to have great potential as an anti-microbial treatment (anti-bacterial and anti-fungal effect) to plant diseases such as in vegetables [25, 26], ornamentals [27], and edible tubers [28]. It also possesses insecticidal properties against various insect pests including fall armyworm (*Spodoptera frugiperda*), sugarcane borer (*Diatraea saccharalis*) [29], rice moth (*Corcyra cephalonica*) [30], legume flower thrips (*Megalurothrips sjostedti*) [31] and cotton bollworm (*Helicoverpa armigera*) [32]. Despite the potential of pepper products, quality maintenance is still a challenge. Therefore, the review discusses the quality attributes of pepper as well as pre- and postharvest factors influencing quality and safety of pepper products. In addition, a brief summary about the strategies to enhance quality and safety of pepper products is presented in this paper.

Quality attributes of pepper

The quality attributes of pepper contributing to its value as a food additive are the volatile oil for aroma and alkaloid compound (piperine $C_{17}H_{19}NO_3$) for pungency [12]. Components of essential oil including alcohols, aldehydes, β-pinene, β-caryophyllene, terpene, limonene, monoterpenoids, diterpenoids and triterpenoids also account for the antioxidant properties and flavour of pepper products [2]. In addition to pungency and aroma, the appearance in terms of colour (dark brown/black) is also an important criterion for grading both the whole and ground pepper form [2,33]. Blackening of peppercorns is considered to be beneficial and an important characteristic in the processing of black pepper product as it relates to its flavour quality. Blackening of peppercorns occurs by enzymatic oxidation of ethanol glycoside (3, 4-dihydroxy phenyl) by an *o*-diphenol oxidase (polyphenol oxidase/PPO activity) found in the fresh green peppercorn skin [34,35]. Apart from polyphenol oxidase activity, decrease in concentrations of phenolic compounds, Vitamin C, and chlorophyll is also linked to blackening of peppercorns [36]. Browning of peppercorns acquired during drying is known to be contributed by colourless phenols present in the skin; thus, the nature and distribution of phenolic compounds make a significant contribution to the quality of black pepper product [2].

Preharvest factors attributing to pepper quality

The quality attributes of pepper such as nutritional composition, flavour, colour and pungency are as crucial as yield [37, 38]. Variations in the chemical composition of essential oils in pepper have been reported and among contributing reasons include varietal differences [1, 38, 39], geographic origin [40], variations in fruit maturity [41], processing methods and procedures [42, 43] as well as storage [2, 44]. The yield and quality of pepper products can be affected by a number of preharvest factors including genetic makeup of the cultivars grown, climatic and edaphic conditions as well as crop management practices applied. Therefore, preharvest factors attributing pepper quality are described below.

Genetic and hormonal factors

Several quality parameters of pepper such as fruit size, shape, colour, biochemical composition and level of bioactive compounds were reported to be genetically controlled [8]. The quality parameters differ from one pepper variety or genotype to another, mainly due to different genetic makeup [1, 39]. Therefore, good quality attributes such as significantly higher levels of oleoresin (≥10%), piperine and volatile essential oil are among the important breeding objectives in pepper [45]. Hu *et al.* [46] reported three major gene groups (I, II and III) associated with piperine production. Group I is made up of glycosyltransferases and shikimate hydroxycinnamoyl transferases genes involved in phenylpropanoid pathway which produce cinnamoyl-CoA for piperoyl-coenzyme-A biosynthesis through amino transfer and elimination of ammonia-lyase and cinnamate 4-hydroxylation reactions. Lysine decarboxylases genes constituted group II involved in L-lysine metabolism, which catalyse the transformation of lysine to piperidine through decarboxylation, amine oxidation, cyclization and reduction reactions. Acyltransferase genes particularly BAHD acyltransferases and serine carboxypeptidase-like acyltransferases compose group III that catalyse the synthesis of piperine in the presence of piperoyl-coenzyme-A and piperidine.

Plant growth hormones are organic compounds that when used in optimum concentrations modify/regulate plants physiological processes in substantial measures [47].

High berry diameter (6.01 mm) was attributed to the increased degree of cell division and differentiation of pericarp, integument and nucellus of the plants due to the action of benzyladenine (BA 50 ppm) [47]. Plants supplied with naphthalene acetic acid (NAA 50 ppm) and BA 75 ppm have high oleoresin (11.40%) and piperine contents (3.99%), respectively [47]. Khew *et al.* [48] found that endogenous growth-regulating substances such as jasmonic acid and salicylic acid in pepper play a role in flowering and fruit setting, whereas auxin, gibberellin and cytokinins are important for fruit growth. Abscisic acid has positive role in fruit maturation and ripening in the development process. Thus, non-synchronous nature of flower development, total fruit development and non-uniform/uneven ripening (differences in ripening period) of pepper berries/fruits within a spike are associated to hormonal effect [48]. Hence, hormones become the primary constraint in pepper production and indirectly affecting the quality of pepper products. Alternate bearing habit of a fruit crop is a behaviour where productivity in 1 year affects productivity in the subsequent year. Flowering site limitations, hormonal control and nutritional control are among the mechanisms that are apparently involved in the maintenance of the alternate bearing condition in fruits [49]. Following a good fruiting/on year, very limited new vegetative growth occurs that generally bears inflorescence, thus limiting flower production in the low fruiting/off year in pepper. The carbohydrates reserve, plant hormones (Auxin-IAA and cytokinin-zeatin riboside) and mineral nutrients have been reported to influence alternate bearing and indirectly hamper the quality of pepper produce [50]. Higher oleoresin content (9.10%) was achieved by 0.5% spray of 19:19:19 complex fertilizer (% N:P:K) than in control (8.72%) indicating that oleoresin levels can be enhanced in off year (by about 5%) through nutrient sprays during preflowering period, thus significantly minimizing the alternate bearing effect in pepper [50].

Climatic factors

Pepper is adapted to areas with optimal climatic conditions. Various pepper-producing areas differ ecologically in air temperature, humidity and rainfall (water availability) due to altitude [39, 51]. Other environmental conditions such as irradiance and soil moisture have been reported to affect photosynthetic functioning of pepper crop, resulting to low productivity and poor fruits quality [52, 53]. A significant location wise variation was reported for both primary and secondary metabolites of dried black pepper berries of variety 'Panniyur-1' in India [40]. Their study showed a clear altitudinal variation in essential oil, oleoresin, piperine, total phenol, crude fibre, starch, total fat and bulk density. Two constituents of black pepper berries, namely β-caryophyllene and total phenol were low at high altitudes (500–1175 masl) and high at low altitudes (10.7–240 masl), while monoterpenes like thujene, α-pinene, sabinene, limonene, α-phellandrene and linalool were relatively high at higher altitudes compared to low altitudes [40]. Essential oil (2.93%; 3.33%), oleoresin (13.21%; 16.18%) and piperine (4.37%; 4.52%) contents of white and black peppercorns of Ciinten pepper variety in Purwakarta district (650 masl) in Indonesia were significantly higher than in Sukabumi district (450 masl) with essential oil of 2.38%; 2.86%, oleoresin (12.52%; 14.17%) and piperine (3.85%; 4.47%) and Ciamis district (190 masl) with essential oil of 2.43%; 2.59%, oleoresin (10.69%; 11.52%) and piperine (3.23%; 3.38%) contents of white and black peppercorns, respectively [39].

Pepper crop management practices

Proper nutrient management ensures availability of essential nutrients during flowering and fruit development. Thus, edaphic factors including availability of essential nutrients are crucial for physiological processes and better quality of pepper. According to Hamza and Sadanandan [54], application of $ZnSO_4$ (0.5%) foliar spray recorded maximum berry zinc (7.4–11.1 mg kg^{-1}) and a significant increase in oleoresin (9.27–11.83%) and piperine (6.9–7.83%) contents irrespective of sources and methods of zinc application (either as chelated forms or as $ZnSO_4$). Potassium (K) is often referred as a quality-enhancing element in pepper production [55]. It indirectly improves nitrogen utilization, protein formation, fruit size, weight, oil content and colour. Srinivasan *et al.* [56] reported that 50% of recommended dose of K applied as sulphate of potash (SOP) for soils with high K status and 100% recommended K applied as SOP + 2% foliar spray for soil with low K status are optimum as an alternate source of K fertilizer. The fertilizer has a potential to supplement significantly higher concentrations of soil K, organic carbon, calcium, sulfur, zinc and copper as well as higher quality in terms of oleoresin (7.99–10%), piperine (5.09–6.02%) and oil (2.57–3.3%) contents of pepper [56]. The study by Tien *et al.* [57] also showed significant increase in pepper quality traits, such as weight (59.5, 60 g) and volume of 1000 peppercorns (108, 109.1 cm^3), fruit density (530, 544 g L^{-1}) and piperine content (4.01, 4.12%) in fruit that was attained at higher K doses 240 and 360 kg K_2O ha^{-1} yr^{-1}, respectively. Nutrient supplied by organic foliar fertilizer alone is insufficient, thus must be used in combination with inorganic fertilizer in order to enhance the production of good quality pepper [58]. Integrated fertilization regime provided a significant increase in physiological functions and quality of pepper [58]. A combination of inorganic fertilizer (NPK) and organic foliar fertilizer (composition of seaweed extract with fish emulsion fertilizer) resulted to a higher grade of pepper quality with the bulk density between 553.21 and 564.48 g/L compared to organic foliar fertilizer alone (455.26 and 479.51 g/L) [58]. This performance was associated to the sufficient nutrients supplied to plants which triggered free amino acid and various types of phytohormone including cytokinin, jasmonic acid, salicylic acid, abscisic acid, oxo-phytodienoic acid and indole-3-acetic acid that could stimulate the physiological functions.

Pepper is a shade-loving plant; therefore, it needs appropriate shading for growth and development. Even under favourable soil moisture conditions exposure to direct sunlight leads to physiological disorders due to high transpiration coefficient during dry period; hence, constant soil moisture is required by pepper plants [52]. Shading influences the amount of light entering the plants' canopy and affects the environmental conditions including air temperature and humidity. The effects of shading on pepper was studied by placing 1–4 black polyethylene shade nets 50 cm above the pepper canopy, resulting in shading intensities of 15%, 30%, 60% and 75%, respectively [52]. The study showed that shading intensity has effect on piperine, volatile oil, total ashes and moisture contents of dried black peppercorns. Moisture content reduced by 19% as shade intensity increased but the amount of moisture was good for fruit storage. Shading intensity of 75% increased piperine content by 19%, and volatile oil content decreased with shading intensity of 15%–30% but increased under the shade intensity of 60%–75%, while total ashes content increased under the shading intensities of 15%, 60% and 75%, respectively [52].

Pepper maturity stages and harvesting methods

Pepper takes approximately 180–230 days (6–8 months) after flowering to reach full maturity, depending on prevailing environmental conditions and variety grown [35]. However, small-scale farmers normally harvest pepper even before maturity, hence compromising the final quality [59]. Usually, harvesting is scheduled based on the kind of required pepper product. In order to achieve a product of good appearance and biochemical composition, it is very important to harvest pepper at the proper maturity stage. Black and green pepper are obtained by harvesting fully matured berries or when one to two berries start turning from yellow to red in each spike. Normally, dried berries having unbroken pericarp constitute black pepper product, while removal of moisture under controlled conditions results to green pepper product. On the other hand, when berries within a spike are fully ripe, then spikes are harvested and berries are processed into white pepper product after removing the pericarp from dried berries. It is crucial to observe fruit maturity indices and ensure the correct time for harvesting, as over-ripe berries will normally fall to the ground [35]. A study by Hu *et al.* [46] revealed that the highest piperine content in berry was at 8 months after pollination (MAP), followed by 6 MAP, 4 MAP and 2 MAP, indicating significance of proper berry maturity for attaining desirable pepper quality. Different methods of harvesting are employed in various pepper producing areas including manual plucking by hands and laying a net above the ground, while berries fall and collected once in every 2–3 days [60]. Nevertheless, manual plucking by hands is commonly practised, where spikes with matured berries are handpicked from plants. Handpicking helps farmers to select only matured, less damaged fruits, and minimizes bruising of fruits that could allow microbial invasion during drying and storage [61]. Pepper plucking equipment has been designed and developed in order to facilitate pepper harvesting [60–63]. Pepper plucking equipment and manual plucking by hand were considered harmless harvesting methods, since no damage to spikes and vines were recorded during evaluation [63].

Postharvest factors influencing the quality and safety of pepper

Postharvest handling plays a great role in the pepper quality maintenance and improvement [64]. The postharvest operations involve threshing, blanching, drying (sun/mechanical), sorting, grading, packaging, storage and processing [65]. Most postharvest factors are controllable and if they get out of hand, they can provide carry-over effects to the remaining value chain of pepper. Hence, precautions must be taken to retain quality and safety at each handling stage. The postharvest factors influencing the quality and safety of pepper are described below.

Blanching and drying

Blanching at 80°C for 2 min is done prior to sun drying to enhance the black shine colour of berries and accelerate the drying process; thus, blanched berries will only require 2 days for sun drying after blanching [64]. Gu *et al.* [34] showed that berries blanched at 100°C for 10 min had the fastest water loss, but the lowest polyphenol oxidase (PPO) activity. Furthermore, the degree of reduced weight percentage and browning in green pepper berries after blanching for 10 min was greater at 100°C than at 90°C and 80°C. Blanching improves colour, removes dust and adheres microbial contamination giving a hygienic product, while pepper volatiles and other chemical loss are minimum [35]. Blanching activates phenolase enzyme responsible for producing black colour as it ruptures the cells and accelerates the escape of moisture from inner core with the help of resinoids pressure on the berry and simultaneously enhances the black colour [35].

Drying is critical stage that decides pepper quality because storage water content is determined at this stage. Since pepper is hygroscopic in nature, and its starch content may subject to mould attack and insect infestation, hence efficient and proper drying is an important process to reduce the mould growth [35]. Once peppercorns are contaminated during drying, other handling practices may also cause additional contamination. Mkojera [61] reported that small-scale pepper farmers in Morogoro district, Tanzania use colour change and experience to decide level of dryness, although such methods are not sufficient indicators of proper drying. Depending upon the climatic conditions, sun-dried pepper berries take 4–5 days for proper drying [65]. Much caution should be taken to prevent overdrying so as to avoid loss of flavour of components and final moisture content should be less than 10% wet bases (wb) [35]. To get a good quality product, it is essential to use proper drying surface. The common surfaces used for dying are bamboo mat, cement floor, and polyethylene fabric [35, 65]. Open sun drying (OSD) on the ground in homestead amplify risk of microbial contamination because of dust and livestock [59]. Whole pepper spikes and berries can be processed in between polythene sheets of 200 gauge for 2–3 h (until they become black) on first day and then sun dried for 3–4 days [66]. This practice allows better recovery of dry berries and good quality berries (good colour, higher aroma, piperine and oleoresin content), and in turn higher market price than whole spikes and berries dried in open sun on cement floor, as well as whole spikes and berries processed by dipping in hot water for 1 min and then sun dried [66]. OSD poses several limitations like exposing the food to contamination, and it is climate-dependent, slow and eventually resulting low market price; thus, utilization of artificial technologies/dryers becomes inevitable [64, 67]. The use of solar tunnel dryer gave better quality (piperine content = 4.5% by weight) with lesser drying time (8 h) than OSD [64]. Green pepper obtained by a sublimation drying method gave more oil (12.1 mg/g) with a significantly higher content of monoterpenes (84.2%) than air-dried green pepper (0.8 mg/g, 26.8%), whereas the oil from ground black pepper contained more monoterpenes, less sesquiterpenes and oxygenated terpenoids compared to green and white pepper oils [44].

Based on response surface methodology, effective drying temperature and duration are essential in designing handling and processing equipment as well as mechanization of the drying process of pepper [67]. Pepper quality was significantly affected by increased drying temperature from 55.86°C to 84.14°C and duration (2.59–5.41 h) as the mass of dried pepper ranged from 6.37 to 1.55 g, bulk density (0.17–0.59 g/ml) and moisture loss (31.1%–84.0%) [67]. The drying kinetics of pepper by oven drying indicate that moisture content decreases with time and drying rate increases with increasing temperature, while drying time decreases as temperature increases since the heat greatly affects the evaporation of moisture to the surrounding and also modifies the characteristic of pepper [68]. An oven drier at 30°C took 2168 min (≈36 h), 40°C (1167 min ≈ 19 h) and 50°C took 801 min (≈ 13 h) to dry the pepper up to the desired moisture content of 7.505% (≈ 12% moisture content of the final product) [68]. Indirect solar-biomass hybrid dryer (S-BHD) can reduce crop losses and improve the quality of the dried product significantly when compared to the traditional methods such as OSD or shade drying [69]. The final dried black pepper in (S-BHD) contained the highest percentage by weight of oleoresin (11.17%/wt), piperine (6.36%/wt) and volatile oil (5.10% v/wt), compared to OSD (oleoresin = 10.53%/wt, piperine = 5.87%/wt and volatile oil = 3.80% v/wt). Microwave drying kinetics showed that drying of pepper under low microwave power level (180 W) can preserve volatile matter in the product and reduce moisture content from 75% to 11% within 88 min compared to several days under OSD [70].

Decortication

Fermentation of ripe pepper fruits used to remove the fruit skin (decortication) was associated with the formation of odour-active compounds (odorants) that resulted to a faecal off-flavour white pepper powder [71]. This study showed butanoic acid (cheese-like odour), 3-methylindole (swine-like faecal odour) and 4-methylphenol (horse-like faecal odour) had the highest flavour dilution factors that attributed an intense faecal/shed-like off-flavour. Moreover, a significant decrease in the typical odour qualities and an increase in the faecal odour were revealed on white pepper stored for up to 7 months. A study on a power-operated decorticator for producing white pepper from black pepper showed that disc speed and soaking time have significant influence on decorticating efficiency and mechanical damage. Softening of pepper skin due to soaking time gives an increase in decorticating efficiency, while softening of the inner core by excessive soaking leads to an increase in the number of broken berries (mechanical damage) and decrease in decorticating efficiency at higher disc speed of a decorticator [72]. The maximum decorticating efficiency (69.52%) was obtained using a grinding stone at disc speed of 71 rpm and 17 h soaking period. There was no much change in the case of oleoresin and piperine content, but there was an increase in the moisture content and was associated to the absorption of moisture by the pepper during soaking prior to decortication. The loss in volatile oil content was attributed to the removal of the creamy outer layer and the oil zone during decortications and the loss of oil in the soaking water [72].

Pepper-associated bacteria for the microbial decortication of fresh ripened berries and dried black pepper for preparation of off-odour-free white pepper have been identified [73]. Dried black pepper decortication (>60%) and fresh pepper berries decortication (98–100%) into white pepper was achieved within 5 days of immersion in bacterial suspension. Much superior-quality white pepper was obtained with *Bacillus subtilis*, *B. licheniformis*, *Acinetobacter baumanii*, *Klebsiella pneumoniae* and *Microbacterium barkeri* [73]. The bacterial isolates secreted multiple hydrolytic enzymes such as cellulase, pectinase, amylase, protease and xylanase. The white pepper thus obtained from bacterial decortication process was free from off-odour compound, especially skatole, while the inherent biochemical constituents of pepper such as oleoresin, essential oils and piperine content were in the acceptable range and were not negatively affected by bacterial decortication [73].

Postharvest treatment

Alternative processing techniques for spices including pepper have been offered by advances in postharvest and storage technology which can enhance biochemical contents. Usage of modern postharvest treatments such as application of ultraviolet-C light (UV-C) to enhance flavour has been explored [74]. Low to medium UV-C doses (1–5 kJ m^{-2}) were subsequently stored within continuously ventilated polypropylene boxes at 5°C for 4 weeks, significantly enhancing flavour compounds (piperine and essential oils) in pepper and colour change (from green to brown). This implies that processing industries can generate more economically sustainable products with reduced impact on the environment, superior biochemical contents that fetch higher prices, and alleviate supply demands [74].

Sorting, grading, packaging and storage

In addition to poor harvesting, lack of produce sorting and grading lead to failure of meeting quality standards, especially for the export markets [59]. Sorting and grading of pepper are based on relative density, colour and size. High-quality pepper is considered to be large, round, with an even black colour, high pungency and complex aroma imparted by high levels of essential oils [75, 74]. Separation of pepper at small-scale level is normally done manually; it is time-consuming and may be ineffective due to human error. A pepper grading machine comprising of vibrating and rotary motion of AC motor was designed and fabricated for sorting and screening pepper based on their size and weight by involving a series of meshes [76]. Pepper storage requires optimal conditions of low temperature, low humidity, free from pests and dry storage. Whole pepper is usually packed in gunny bags and polyethylene-lined double burlap bags [35]. Dried whole pepper (10–12% wb) should be stored in jute gunny bags with polyethylene lining (>0.003 inch) or in laminated bags, while polypropylene package for ground pepper [35]. The effect of storage facility and period on the essential oil amount and the composition of the oil isolated from black, green and white pepper have been studied [44]. After 1 year of storage in glass vessel at room temperature, the amount of oxygenated terpenoids increased, while the amount of isolated oils and terpenes decreased. Compared to white and black pepper, the amount of oil in green pepper raised more than twice for both sublimation and air-drying methods during 1 year of storage in a glass vessel at room temperature [44].

Grinding

The quality of powdered product is significantly affected by grinding machine (such as hammer mill) and feed temperature [77]. An increase of 1%–3% moisture was observed for the ultra-low feed temperature (−3.33°C–12.86°C) helped to increase oleoresin yield (2%–3%), volume surface mean diameter of black pepper powder (0.15–0.18 mm), higher retention of oil monoterpenes and volatile oil content (17%). Regulation of pepper processing particularly grinding is inevitable. The availability of heavy metals from machinery influences and changes the levels of heavy metals (Fe, Pb and V) in pepper products that can exceed the maximum acceptable levels. Krause *et al.* [78] showed that ground black pepper had higher levels of trace elements than products commercialized as peppercorn: Fe (peppercorn: 16.6–137 mg/kg; ground: 69.8–1147 mg/kg), Pb (peppercorn: 10.9–88.4 μg/kg; ground: 21.3–947 μg/kg) and V (peppercorn: <20.3–141.7 μg/kg; ground: 64.1–1072 μg/kg).

Essential oil extraction

The quality of the essential oil is of great concern simply because the extensive use of pepper essential oil in therapeutic applications. The essential oil yield through supercritical fluid (SFE) extraction was significantly enhanced as pressure increased (90–150 bar) and temperature decreased (50–40°C), while the oil extraction rate increased with increasing flow rate (1.1–3 kg/h) than that obtained through hydro-distillation [42]. Supercritical carbon dioxide (SC-CO_2) extraction method impedes the degradation of thermolabile constituents in essential oil than a hydro-distilled essential oil [43]. The SC-CO_2 was more selective thus produced an essential oil with superior antioxidant activity, and was successfully attained at 30 MPa, 40°C and 40 min. Thus, SC-CO_2 could also be an option for obtaining essential oils of higher quality (antioxidant compounds) with respect to the independent extraction variables mainly pressure, temperature and dynamic extraction time.

Biological and chemical contaminants of pepper

Globally, the biological (microbes and other organisms) and chemical contaminants (secondary metabolites, i.e. mycotoxins particularly aflatoxins (AFs) and ochratoxins (OTs) produced by fungi, toxic elements such as heavy metals and pesticide residues) have earned major concern in economic and public health. Similar to other agricultural products such as maize and groundnuts [79], pepper may also be subjected to contamination from environmental pollutants such as heavy metals, chemical agents, that is plasticizers, BPA (bisphenol A, 2,2-bis-4-hydroxyphenyl propane), polycyclic aromatic hydrocarbons (PAHs) and pesticides as well as presence of aflatoxins/moulds producing toxic secondary metabolites [80, 81]. The mycotoxins, that is AFs and ochratoxin A (OTA), pesticides (chlorpyrifos and triazophos) and the dye Sudan I pose the highest human-health risk in the selected herbs and spices including black pepper, owing to their severe acute toxic effects, that is acute reference dose (ARfD) and frequent probability of occurrence (based on historical data), hence ranked as high priority hazards [82].

Mycotoxins

AFs and OTs are a family of poisonous substances (mutagens/carcinogens) produced by fungi (moulds) which grow in soil, decaying vegetation, hay and agricultural crops [83]. *Aspergillus* spp. and *Penicillium* spp. are the main fungi producing AFs and OTs, and are abundant in warm and humid regions of the world [84]. Garduño-García *et al.* [81] found that green, white and black peppers from markets in Egypt, India, Turkey and Mexico City were contaminated with at least one aflatoxin, namely B_1, B_2, G_1 or G_2. Absence of normativity in these countries on this issue averts the reduction of aflatoxins concentration in human diet. According to Garduño-García *et al.* [81], green pepper was the most contaminated due to the degree of ripening and less commercial, hence stored for a longer period of time, thus increasing the risk of mycotoxigenic fungal growth. However, black pepper had an intermediate level of contamination due to high level of essential oil (piperine) and other volatile compounds, hence was not good substrate for AFs biosynthesis (as it inhibits fungal growth and mycotoxins production). White pepper was the least contaminated, owing to polishing, that is removal of outer skin from dry black pepper [81].

Heavy contamination by *Aspergillus*, *Rhizopus*, *Penicillium* and *Fusarium* fungal species at level of 2200 to >30000 cfu/g was detected on dried black peppercorns from Morogoro district of Tanzania [61]. Nguegwouo *et al.* [85] reported OTA levels below the EU limits of 15 μg/kg and tolerable daily intake value of 17 ng/kg bw/day in black (1.15–1.91 μg/kg; 0.182 ng/kg bw/day) and white (1.81–4.89 μg/kg; 0.699 ng/kg bw/day) pepper products sold in Yaoundé city markets in Cameroon. Zareshahrabadi *et al.* [86] reported OTA >15 μg/kg limit, dominated by *Aspergillus* species, followed by *Penicillium*, and Mucor species in black pepper products from markets in Shiraz, the south part of Iran (one of the main importers and consumer of spices, worldwide). Lower levels of OTA ranging from 0.05 to 13.15 μg/kg were detected in black pepper marketed in Brazil (one of the largest producers in the world). The potentially ochratoxigenic species present in 80% of black pepper products were frequently dominated by the OTs A. section Nigri, followed by A. section Circumdati specifically; *A. niger*, *A. welwitschiae*, *A. carbonarius*, *A. westerdijkiae* and *A. ochraceus* and *A. pallidofulvus* [87].

The occurrence of AFs and OTs species on pepper products indicates improper handling at some stages of the production chain, poor harvesting practices, inappropriate storage (i.e. pepper is generally stored at room temperature and for prolonged periods with conditions suitable for fungal growth and mycotoxin production) as well as lack of good conditions during transportation, marketing and/or processing [85, 61]. Hence, it indicates the need for regulatory bodies to ensure regular effective surveillance, quality control procedures, and continuous monitoring of pepper and empower the food-related laboratories with precise methods and equipment for isolation and detection of mycotoxins in order to protect consumers' health [86, 87].

Various studies have reported on the influence of handling practices and levels of awareness and knowledge on mycotoxin levels in common staple crops such as maize, groundnuts [88] and other spices including ginger and cloves [89]. Limited studies have focused on customers' perception, farmers' awareness and knowledge of aflatoxins in pepper. Blanching, rubbing spoiled/contaminated pepper with cooking oil, washing with cold water and re-drying in the sun as poststorage treatment along with high moisture content (13.8%) were highly related to small-scale farmers' unawareness on mycotoxins [61].

Heavy metals

Different parts of plants have the ability to store heavy metals that enter through the biological cycle of plants. Even at very low concentrations, the dietary intake of contaminated plants with inorganic substances, that is heavy metals are highly toxic and consequently endanger the health of humans and animals. According to Ahmad *et al.* [90], spices including pepper are frequently contaminated with the most common toxic metals such as cadmium (Cd), arsenic (As), mercury (Hg) and lead (Pb). Accumulation of heavy metals in human body system is associated to cause kidney damage, anaemia, lower sperm count, miscarriage, neurological disorders, hepatotoxicity, cancers, haemorrhagic trauma, respiratory distress, cardiovascular diseases, atherosclerosis, hypertension, glycaemic index disturbances, renal and liver diseases, reproductive diseases and dermatological disorders [90]. The levels of heavy metals such as Pb (0.32 ± 0.22 mg/kg), Cd (0.14 ± 0.06 mg/kg) and Cr (0.33 ± 0.16 mg/kg) on dried black peppercorns from Morogoro district of Tanzania were below permissible levels [61]. The detection of heavy metals in the analysed samples was highly related to postharvest practices, particularly storage. Farmers stored peppercorns along with other materials that could cause cross-contamination [61]. This study also endorses the significance of hygienic harvesting and postharvest safety in minimizing the risk of heavy metal contamination.

Plasticizers, BPA and PAHs

Plasticizers are applied for improving elasticity, flexibility, colour, resistance and durability of different plastics polymers in food packaging, while BPA is a monomer used in the synthesis of polycarbonates, polyesters and epoxy/phenol resins found in plastic bottles and in the lining of food cans [91]. PAHs are a large class of organic compounds that is composed of two or more fused aromatic rings of carbon and hydrogen atoms [92]. The plasticizers, BPA and PAHs are considered as threats to human health due to extensive use in food packaging, potential migration into foods including spices and longer period persistence in human body tissues. They contribute to cancers, allergies, endocrine disorders and alterations in the reproductive system [80].

Plasticizers residues mainly di-(2-ethylhexyl)phthalate (DEHP = 1.18 ± 0.74 μg/kg), di-butylphthalate (DBP = 0.24 ± 0.11 μg/kg), di-methyladipate (DMA = 0.46 ± 0.23 μg/kg), di-ethylphthalate (DEP = 0.54 ± 0.35 μg/kg) and di-(2-ethylhexyl) terephthalate (DEHT = 1.9 ± 0.72 μg/kg) were recorded lower than their limit of quantification (LOQ = 10 μg/kg) in locally produced and unpackaged black pepper from Algeria, Tunisia and Italia, whereby no hazardous quantities of these contaminants were assumed through feeding [80, 91]. For herbs and spices that are produced locally and not packaged, the possible sources of exposure to plasticizers and BPA residues are related to their disposal from the plastics used in the production cycle [91]. The plasticizers and BPA migrate into the environment during production, distribution phases, usage and disposal. Aqueous leaching from plastics and waste, incineration of plastic waste, volatilization from resin matrices and wet deposition from the atmosphere promote the introduction of the plasticizers and BPA into the environment [91].

The commercial blends of black pepper originating from Brazil and Vietnam showed the sum of four PAHs mainly benzo[a]pyrene (BaP), benz[a]anthracene (BaA), benzo[b]fluoranthene (BbF) and chrysene (Chr) content (ΣPAH4 = 1.39 to 25.18 μg/kg) lower than the EU MRL (50 μg/kg), whereas the dominant PAH was Chr (0.76–10.91 μg/kg, followed by BbF (0.51–7.19 μg/kg), BaA (0.09–7.25 μg/kg) and BaP (<0.05–6.60 μg/kg) levels below the EU MRL (10 μg/kg) [93]. The pretreatment process whereby unripe pepper berries are boiled in hot water for a short period before drying leads to rupturing of cell walls, thus accelerating browning during drying, and consequently exposes pepper to PAHs contamination [93]. The major pathways for the formation of PAHs and contamination of spices include usage of polluted water or contaminated soil during crop production, incineration of agricultural waste, burning of biomass and contact with low-quality mineral oil along with the deposition of air particulates during the postharvest and processing stages [93].

Pesticides

Application of agricultural chemicals especially synthetic pesticides in high dosage and frequency for prevention of crop damage and losses inflicted by pests on pepper crop has been promoted due to intensive cultivation, that is to achieve high yields [94]. The study by Yap and Jarroop [95] in Malaysia, reported low level of chlorpyrifos residue (<10 μg/kg to 392.07 μg/kg), maximum residue level (MRL = 0.5 mg/kg) and preharvest interval (PHI = 13 days) for safe consumption of black pepper berries after application for one fruiting cycle. Yao *et al.* [96] found that black pepper collected from province markets in China contained residues of pesticides clothianidin (0.02 mg/kg) and acetamiprid (0.03–0.07 mg/kg) below the European (EU) MRLs (0.1 mg/kg), but the residues of carbendazim (0.18–0.50 mg/kg) and metalaxyl-M (0.03–0.73 mg/kg) exceeded the MRLs.

The pesticides chlorpyrifos and triazophos residues in the selected spices (including black pepper) frequently consumed in EU exceeded MRL, and hence have been classified as high-priority compounds [82]. These compounds may cause severe acute effect on human health (i.e. low ARfD). However, carbendazim, cypermethrin, dimethoate, endosulfan and ethion were classified as medium-priority compounds (their toxicity classified as less severe than for chlorpyrifos and triazophos) although they were frequently reported in rapid alert system for food and feed (RASFF) and/or found at levels above the MRL. Bifenthrin, DDT (4,4′-dichlorodiphenyltrichloroethane), metalaxyl, profenofos, propamocarb, tefluthrin and trifluralin were classified as of low priority; however, metalaxyl and profenofos have a high probability of occurrence, but these have low impact on human health, while tefluthrin has low probability of occurrence in the selected spices, but may have severe effects on human health. Intensive use of synthetic pesticides has serious implications for the health of the farmers, consumers, livestock and the environment. Therefore, synthetic pesticides may be applied provided that global agricultural practices (GAP) are followed, such that prescribed withdrawal periods are maintained in order to ensure that levels in the final products are below the MRLs [82].

Strategies to enhance the quality and safety of pepper

Pepper is consumed in minimal amounts as a flavour enhancer; hence, the contribution of aflatoxins and heavy metals is relatively low in comparison to other agricultural products, such as cereals, legumes, fruit, vegetables and dairy products [81]. However, there is a need for collective efforts among producers, supplies and consumers to enhance the reduction of aflatoxins and heavy metals level in pepper. Therefore, strategies to enhance quality and safety of pepper are described below.

Storage conditions and duration

In order to provide pepper that meets the required safety standards, more emphasis has been on usage of good manufacturing practices in producing ground pepper, conducive storage conditions such as temperature and duration, since the products stored at a low water activity (A_w) alone may not efficiently prevent the survival of MOs [97]. A significant reduction in counts of the *Salmonella rubislaw* strain, most probable number (MPN) per gram used to contaminate the ground pepper was achieved at higher storage temperatures 35°C (3.9 MPN/g), 25°C (2.6 MPN/g) than at 5°C (1.2 MPN/g) and at higher A_w = 0.887 (3.5 MPN/g) than by low A_w = 0.663 (1.994 MPN/g) and at 15 days (3.1 MPN/g) than 2 days (2.1 MPN/g) of storage [97]. Keller *et al.* [98] showed that at high relative humidity (97%), A_w increased to approximately 0.8–0.9 after approximately 20 days and no *Salmonella* was detected after 45 and 100 days at temperatures 25°C and 35°C. Under ambient humidity (≤40%) and temperatures (25 and 35°C), populations showed an initial decrease of 3–4 log cfu/g (colony forming unit per gram), then remained stable for over 8 months. This evidenced that *Salmonella* can readily grow at permissive A_w in ground black pepper and may persist for an extended period of time under ideal storage conditions.

Decontamination methods

In comparison to water-rich foods, microorganism (MO) inactivation in dried products is challenging, mostly because of increased MO resistance in low-water activity foods including pepper [99]. Pepper may reach consumers presenting poor quality, due to microbial contamination or insect infestation, and loss of volatile compounds [97]. There are several technologies commonly used for decontamination of pepper, and have shown significant MO reduction. Nevertheless, the technologies have numerous limitations, including alterations of product quality (aroma and colour), environmental impacts, carcinogenic potential and/or lower consumer acceptance. Strategies to enhance safety of pepper products are described below.

Irradiation treatments and dry sterilization

Gamma-irradiation of powdered black pepper at doses of 5 kGy reduced the microorganisms (coliforms, yeasts and moulds) to less than 1 cfu/g 3 months after storage, and there were no remarkable changes in volatile oil contents at radiation doses of 5 kGy and 10 kGy [100]. The extracts from the gamma-irradiated powdered black pepper were pale yellowish liquids with a characteristic, terpenic, powerful odour of black pepper trait. These doses were toxicologically and nutritionally confirmed as safe maximal dose. On the other hand, the number of MO was multiplied by one order in the heat sterilized (dry steam, 130°C, 3 min) powdered black pepper during the same storage period. The extracts of the heat sterilized powdered black pepper was darker coloured, with less strong overall odour/aroma, and induced a significant decrease of some volatiles [100]. The aroma active compounds (potent odorants) in pepper, mainly linalool, piperitone, and β-damascenone had the most reduced flavour dilution factor (FD = 10) in association with the decrease of thermolabile volatiles caused by the heat sterilization [100]. Compared to the dry sterilization at 130°C, microwave irradiation treatment (at a power level of 600 W) exhibited better results in terms of black pepper decontamination [101]. Maximum decontamination was achieved in microwave irradiation for 3 min by inducing a 26% decrease in total mesophilic aerobic bacteria (TMAB) number (3.89 to 5.78 log cfu/g) and bacterial spore (3.70 to 6.08 log cfu/g). With dry sterilization for 30 and 60 min period, the number of TMAB was in the range of 5.29–6.64 log cfu/g and bacterial spore number ranged from 5.24 to 6.66 log cfu/g, likely due to very short time of treatment and smaller reduction of water content inside pepper. Conversely, prolongation of the dry sterilization treatment for 90 min exhibited affirmative effect on TMAB and bacterial spore reduction, indicating time of treatment as an important factor in dry sterilization [101]. Exposure of whole black pepper with gaseous ozone (ozonation process) at optimum conditions of flow rate (1 L/min) and exposure time (10 min) significantly resulted to maximum reduction of the total microorganism (3–4 log cfu/g) with minimum changes in piperine levels [102].

Atmospheric pressure plasma treatments

A combination of storage at temperatures 25°C and 37°C, relative humidity 33% and 97% and 80 s of atmospheric pressure plasma (APP) treatment reduced *Salmonella* strains (6.5–8.79 $\log_{10}$) and slight changes to the colour of black peppercorns were observed [103]. Neither direct nor indirect cold atmospheric pressure plasma (CAPP) treatment significantly affected the surface colour or the quality parameters (volatile oil content and the main aroma compound piperine) despite the significant inactivation of native microbial flora of black peppercorns [104, 105]. Indirect air-plasma treatment for 30 min inactivated the spores of *Salmonella enterica* (4.1 $\log_{10}$), *B. subtilis* (2.4 $\log_{10}$) and *Atrophaeus* (2.8 $\log_{10}$) [104]. Similarly, higher inactivation of native microbial flora of black peppercorns (>4.0 $\log_{10}$) was attained after 60 min indirect treatment with air-plasma [105]. High-pressure/compressed gases such as oxygen (10 MPa) and carbon dioxide (5 MPa) at 70°C–100°C resulted to microbial reduction in powdered white and black peppers, whereby the degree of microbial reduction in pepper was dependent on the temperature and duration of treatment [106]. Mesophilic aerobic bacterial counts of less than 103 cfu/g in white and black pepper were achieved with gas pressurization at 100°C for both at 10 and 40 min. The reduction in the microbial population of the pepper products was ascribed to the microbicidal effects of high-pressure gas and heat treatment. On the other hand, the piperine content decreased by approximately 10%, and the lightness values decreased markedly, indicating a darker colour in both treated white and black pepper than in untreated. The relative absorbance ratio of β-pinene, *p*-cymene, sabinene and α-pinene was below 1 in treated products compared to untreated. Piperine content was slightly higher in pepper treated with carbon dioxide than with oxygen but the difference was not significant. Compressed oxygen produced new aldehydes, isobutanal and 2-methylbutanal, but these compounds were not detected after carbon dioxide pressurization, hence vivid qualitative alterations in volatile compounds [106].

Vacuum-assisted steaming and fumigation

In order to improve the safety and quality of pepper, Newkirk [107, 108] investigated the inactivation of *Salmonella enterica* and *Enterococcus faecium* using vacuum-assisted steam (dry steam) and commercial chemical fumigant ethylene oxide (EtO). The vacuum-assisted steam significantly reduced *S. enterica* and *E. faecium* in biofilm inclusion (4.8 ± 0.19, 4.7 ± 0.19 log cfu/g) and TSA-grown inoculation methods (6.3 ± 0.18, 5.3 ± 0.18 log cfu/g). On the other hand, EtO fumigation significantly reduced total aerobic plate counts by 3.42 ± 0.38 log cfu/g. It also, reduced the mean populations of *Salmonella* (6.62 ± 0.62 log cfu/g) and *E. faecium* (2.96 ± 0.62 log cfu/g), and the distribution of inactivation of *Salmonella* between black peppercorns bags varied between 2.02 and 8.34 log cfu/g.

Radiofrequency pasteurization

Due to the high temperature realized within 10 s, extra higher log reductions were effectively attained for *Salmonella* spp. (2 log cfu/g) and *E. faecium* (1.6 log cfu/g) bacteria at 130 s than 120 s of radiofrequency (RF) pasteurization [109]. The RF pasteurization reduced *Salmonella* from whole peppercorn (5.31 log cfu/g) and ground black pepper (5.98 log cfu/g). The products did not experience a considerable change in quality (colour, piperine, total phenolic, volatile oil and the antioxidant activity) after RF heating.

Pepper quality and safety standards

Although spices including pepper are utilized at quite low quantities, they can still pose health threat to consumers especially when contaminated with mycotoxins or adulterated with harmful colourants [110]. Usually, pepper is added as an ingredient to various processed foods or cooked dishes, therefore if contaminated can cause extensive impact because of the potential to contaminate diverse products along the food chain [111]. Therefore, quality and safety standards for pepper are established to increase product market by controlling quality/value, preventing unfair trade and protecting consumers and environment [112]. The standards also ensure that cultivation, harvesting, transportation and further treatments prevent adulteration, and contaminations and meet the market requirements [113, 114].

The American Spice Trade Association (ASTA) [115], European Spice Association (ESA) [113], International Pepper Community (IPC) [116], Bureau of Indian Standards (IS 1798:2010) [117] and Tanzania Bureau of Standards (TBS: TZS 30–2013) [118] are some of the adopted standards in pepper commercialization. In the international market, quality specifications for trade are laid down by the importing as well as the producing countries. Each nation or region establishes its own standards taking into account the specific conditions of its citizen and environment. The adopted standards allow for assessment of pepper based on physical quality properties, that is size, shape, colour, odour, taste, etc., as well as chemical quality attributes such as moisture, piperine, volatile oil, ash contents, etc. (Table 1) and microbiological quality properties (Table 2). The quality parameters that have been well-defined in standards of particular countries/regions indicate that they are of more relevance to the context of pepper quality. Therefore, this needs to be comprehensively reviewed by other countries/regions whose standards are missing those quality parameters [110–112]. The physical and microbiological quality parameters not defined in various standards, may indicate that these parameters are not considered important, but there is a need for review by the responsible regulatory agencies [112]. For specific contaminations, the corresponding MRLs are referred to other guidelines, existing international standards or national legislations [110, 111].

National standards are derived from the international or regional standards either by direct application or modification to suit local conditions [112]. The international standards, however, are adopted to overcome technical barriers in international commerce when different nations come together with mutually incompatible technical regulations and standards that are developed independently and separately by each nation. Hence, the United Nations FAO/WHO Commission has the mandate to establish a collection of internationally adopted standards, guidelines and related codes of practices that are known as Food Laws/Codes or *Codex Alimentarius* (in Latin), for example the 'Standard for black, white and green peppers' (CXS 326–2017) [114]. The Codex Alimentarius applies to black, white and green pepper for both direct consumption and ingredient in food processing or repackaging. Codex Alimentarius allows for assessment of pepper based on basic properties including colour, flavour, odour, berry size and shape as well as physical and chemical quality properties (Table 3). However, for microbiological quality properties assessment, products covered by 'Codex Alimentarius' shall comply with the maximum levels of the 'General Standard for Contaminants and Toxins in Food and Feed (CXS 193-1995)' [114].

Conclusions

Quality and safety of pepper are influenced by the preharvest factors such as genetic, hormonal, variation of climatic conditions due to altitude, crop management, soil

Table 1. Physical and chemical quality properties of pepper adopted in regional and national standards.

	ASTA		ESA (Quality Minima)			IPC	Tanzania		India				
	Whole pepper		Whole pepper				Whole pepper		Black pepper (Whole)			White pepper	
	White	Black	Black	White	Green	Whole pepper Black	White	Black	NP/SP[1]	Processed	Ground	Whole	Ground
Physical quality properties													
Size/diameter (mm)[2]	2.0–6.0	2.5–7.0	2.5–7.0	2.0–6.0	2.0–6.0	2.5–7.0	3.0–6.0	3.0–6.0	2.5–7.0			2.0–6.0	
Colour	Matt grey, Brownish/ Pale ivory white	Brown-black/black	Brown-black/black	Matt grey, Brownish/ pale ivory white	Green, Greenish/ Dark-greenish	Brownish-Darkbrownish/ black	Mattbrownish, pale ivory white	Brown, grey/black	Brown, grey/black			Light brown, white	
Organoleptic taste	Sharp, penetrating, pungent	Hot, biting, pungent	Hot, biting, pungent	Sharp, aromatic	Pungent	Hot, biting, pungent	Slightly sharp, very aromatic	Sharp, aromatic	Fresh, pungent, aromatic			Aromatic	
Extraneous matter (% m/m)[3] max.[4]	0.5	1.0	2.5	1.0	1.2	2.0	0.8	1.5	1.0	1.0		<0.8	<0.8
Organic extraneous matter (% m/m) max.									0.8				
Inorganic extraneous matter (% m/m) max.	1.0	1.0	2.0	2.0		1.0			0.2				
Light berries (% m/m) max.	2.0	10.0	2.0	2.0		2.0		10.0	10.0	5.0			
Pinheads (%) max.		4.0	3.0			4.0		4.0	5.0	4.0			
Broken berries (% by weight)[5]	2.0	2.0		4.0		4.0						<3.0	
Black berries (% by weight)	3.0			15	5.0							<5.0	
Insect damaged matter (% by weight)	1.0	1.0	Not allowed	Not allowed	Not allowed	2.0	Not allowed	Not allowed	1.0	1.0	1.0	<1.0	<1.0
Chemical quality properties													
Bulk density (g/L)[6] min.[7]			500	600		550	600	490	450	490		600	
Moisture (%) max.	12.0	10.8	12.0	12.0	13.0	12.0	12.0	12.0	12.0	12.0	12.0	<13	<13
Total ash on dry basis (% m/m) max.	3.5	6.0	7.0	3.5	3.0	7.0	3.5	6.0	7.0	6.0	6.0	<3.5	<3.5

Acid insoluble ash (% w/w)[8] max.	0.3	1.5	1.5	0.3	0.3		0.3	1.2	1.2	1.2	1.2		<0.3
Non-volatile ether extract (% m/m) min.	7.0		7.0	6.5		7.0	6.5	6.0	6.0	6.0	6.0	≥6.5	≥6.5
Volatile oil (% mL/100 g)[9]	2.0	2.0	2.0	1.5	1.0	2.0	1.0	2.0	2.0	2.0	2.0	≥1.0	≥0.7
Piperine content (% m/m) min.	5.0	5.0	3.5	4.0		3.0–4.0	4.0	4.0	4.0	4.0	4.0	≥4.0	≥4.0
Crude fibre, insoluble index (% m/m) max.							6.5	17.5			17.5		<6.5

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[1] NP = Non-processed; SP = Semi-processed.
[2] mm = millimeter.
[3] % m/m = per cent mass/mass.
[4] max = maximum
[5] % by weight = per cent by weight.
[6] g/L = gram per liter.
[7] min = minimum.
[8] % w/w = per cent weight/weight.
[9] % mL/100 g = per cent milliliter/100 grams.

Table 2. Microbiological quality properties of pepper adopted in regional and national standards.

	ASTA		ESA	IPC	Tanzania	India
	Whole pepper		Whole pepper (White/Black)	Whole pepper (Black)	Whole pepper (white/black)	Whole pepper (black/ white) NP/SP[1], Processed/ground
	White	Black				
Microbiological/Contaminants						
Whole insects dead (by count)	2.0	2.0	Not allowed	Not allowed	Not allowed	Shall be absent
Excreta mammalian (mg/lb)[2]	1.0	1.0	Not allowed	Not allowed	Not allowed	Shall be absent
Other excreta (mg/lb)	1.0	5.0	Not allowed	Not allowed	Not allowed	Shall be absent
Mould (by weight)	1.0	1.0	Not allowed	3.0	Not allowed	Shall be absent
Insects defiled/infested (% by weight)[3] max.[4]	1.0	1.0	Not allowed	2.0	Not allowed	1.0
Salmonella (in 25 g)	Not allowed	Not allowed	Not allowed	Not allowed	Shall be absent	Shall be Absent
Yeast and mould (No./g)[5] max.			10^6		10^3	
Escherichia coli (No./g) max.			10^3	<3	Shall be absent	
Aflatoxin total B1 (ppb)[6] max.	2.0	2.0	5.0			
Aflatoxin total B1 + B2 + G1 + G2 (ppb) max.	4.0	4.0	10.0	20		30.0
Ochratoxin-A total			< 30.0			
Mesophilic aerobic bacteria (total count)			< 30.0		10^5	

[1] NP = Non-processed SP = Semi-processed.
[2] mg/lb = milligram per pound.
[3] % by weight = per cent by weight.
[4] max = maximum.
[5] No./g = numbers per gram.
[6] ppb = parts per billion, 1 ppb = 1 μ/kg.

Table 3. Physical and chemical quality properties of pepper adopted in Codex Alimentarius.

	Whole Pepper (Black) Class/Grade			Whole Pepper (White) Class/Grade			Whole Pepper (Green) Class/Grade		
	I	II	III	I	II	III	I	II	III
Physical characteristics									
Bulk density (g/L)[1] min.[2]	550	500	400	600	600	550	NA	NA	NA
Light berries (% m/m)[3] max.[4]	2.0	5.0	10.0	1.0	2.0	2.0	NA	NA	NA
Extraneous vegetable matter (% m/m) max.	1.0	2.0	2.0	1.0	1.5	2.0	0.5	1.0	1.2
Foreign matter (% m/m) max.	0.1	0.5	0.5	0.1	0.5	0.5	0.1	0.5	0.5
Black berries/corns (% m/m) max.	NA[5]	NA	NA	5.0	7.5	10.0	Nil[6]	Nil	5.0
Broken berries (% m/m) max.	NA	NA	NA	2.0	3.0	3.0	1.0	3.0	10.0
Mouldy Berries (% m/m) max.	1.0	2.0	3.0	1.0	2.0	3.0	Nil	1.0	2.0
Insect defiled berries (% m/m) max.	1.0	1.0	2.0	1.0	1.0	2.0	0.5	1.0	2.0
Mammalian/other excreta (mg/kg)[7] max.	1.0	1.0	2.0	1.0	1.0	2.0	1.0	1.0	2.0
Pinheads for black pepper (% m/m) max.	1.0	2.0	4.0	NA	NA	NA	NA	NA	NA
							Whole pepper	**Ground pepper**	
Chemical characteristics	**I**	**II**	**III**	**I**	**II**	**III**	**(Green)**	**Black**	**White**
Moisture content (% m/m) max.	12.0	12.0	13.0	12.0	12.0	13.0	12.0	12.0	13.0
Total ash, dry basis (% m/m) max.	6.0	7.0	7.0	3.5	4.0	4.0	5.0	6.0	3.5
Non-volatile ether extract (% m/m) min.	7.0	7.0	6.0	6.0	6.0	6.0	0.3	6.0	6.0
Volatile oils on dry basis (% mL/100 g)[8] min.	2.0	1.5	1.0	1.5	1.5	1.0	1.0	1.0	0.7
Crude fibre insoluble index (% m/m) max.	Nil	Nil	Nil	Nil	Nil	Nil	Nil	17.5	6.5
Piperine on dry basis (% m/m) min.	3.5	3.0	2.0	4.0	3.5	3.0	NA	3.5	4.0
Acid insoluble ash (% m/m) max.	1.5	1.5	1.5	0.3	0.3	0.3	0.3	1.2	0.3

[1] g/L = gram per liter.
[2] min = minimum.
[3] % m/m = per cent mass/mass.
[4] max = maximum.
[5] NA = Not applicable.
[6] Nil = no value.
[7] mg/kg = milligram per kilogram.
[8] % mL/100 g = per cent milliliter/100 grams.

fertility, shade intensity, maturity stage and harvesting methods. Postharvest practices mainly blanching, drying, decortication, postharvest treatment, sorting, grading, packaging as well as processing methods (grinding and essential oil extraction) and storage conditions are also of high importance. Pepper moisture level, colour, size, essential oil, oleoresin, piperine, bulk density, monoterpenes (thujene, α-pinene, β-caryophyllene, sabinene, limonene, α-phellandrene and linalool), total phenol, odorants (butanoic acid, 3-methylindole and 4-methylphenol) as well as presence of mycotoxins (AFs and OTs), heavy metals, plasticizers, BPA, PAHs and pesticides are attributed to pre- and postharvest factors. These findings have significant implications on the trade of high-quality pepper, safety of producers, consumers and the environment. Therefore, more precautions have to be taken to regulate shade, drying temperature and duration, soaking duration, hygienic processing and storage in order to retain quality, minimize the risk of contaminations and comply with the standards. It is also necessary for the regulatory bodies to enhance effective surveillance and quality control procedures regarding pepper contaminants and empower the food-related laboratories with precise methods and equipment for isolation and detection of contaminants.

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