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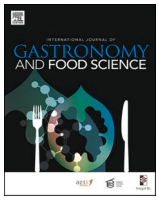

The king of spices: On pepper's pungent pleasure

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ABSTRACT

Pepper (*Piper nigrum* Linn.), and its key pungent constituent piperine (an alkaloid), has long been one of the world's most popular spices. Interestingly, it is one of the only culinary spices (along with the mineral salt) that is to be found on/at the dining table around the world. Known as the 'king of spices', pepper possesses a number of beneficial anti-microbial and anti-carcinogenic properties, as well as a gustatory pungency that chefs and consumers in many countries have long found highly-desirable. Given that pepper is already found on many dining tables around the world, together with the fact that it delivers a pungent boost to the flavour of food (without any of the obvious negative health consequences, or adverse public perception, of other flavour enhancers such as monosodium glutamate or kokumi), it would appear to be ideally positioned as a healthy flavour enhancer, one that also allows the consumer to personalize their tasting experience. That said, the results of research where pepper has been added directly to a recipe, rather than the consumer adding it themselves, have not always given rise to a positive result, suggesting that the ability to add it oneself (i.e., to taste) may play an important part in the consumer's overall enjoyment of the flavour of this spice.

1. Introduction

Black pepper (*Piper nigrum* L.), sometimes referred to as the 'king of spices' (e.g., Hammouti et al., 2019; Milenković and Stanojević, 2021; Nair, 2004, 2020; Ravindran and Kalluparackal, 2000),[1] has long been a highly-valued and popular culinary spice (e.g., Ravindran, 2000a, b; Simmons, 2021; Spence, 2021). Ravindran and Kalluparackal (2000, p. 62) write that: "Among the spices, black pepper is the king. It is the most important, most popular and most widely used spice in the world." As early as 3000 BCE, the Babylonians and Assyrians were already trading black pepper and other spices with the peoples of the Indian subcontinent. According to Van der Veen and Morales (2015), while spices were used in antiquity in a ritual setting (e.g., funeral rites, offerings), in perfumery, and in medicinal remedies, black pepper was the only tropical spice that was used regularly in a culinary setting. Overland trade stretching back at least 3500 years is mentioned in Egyptian papyruses (see McGee, 1984/2004, p. 427; Freedman, 2008). In fact, according to the Bible, when the Queen of Sheba visited King Solomon (BC 1015–66), she arrived bearing the gift of a caravan of spices, comprising primarily black pepper (Milenković and Stanojević, 2021). It has been suggested that black pepper was the first oriental spice to have been introduced into the Western world (Lawless, 1989), and was well-known amongst the Romans and Greeks (Ravindran and Kalluparackal, 2000, p. 62).

Pepper has seemingly managed to retain its position as one of the world's most popular spices through the millennia (e.g., Freedman, 2020; Hertzmann, 2021; Lawless, 1989; O'Donnell, 2021). In the Middle Ages, pepper assumed great importance throughout Europe (Ravindran and Kalluparackal, 2000, p. 62). In fact, it's said to have given rise to revolutionary changes in Western cooking. According to Lawless (1989), pepper represents about 40% of the retail spice business in the US. Of the total spices that are traded internationally, black pepper accounts for about 34%, with demand continuing to rise to unprecedented levels (Weil et al., 2021).[2] Nair (2020, p. vii) predicted that global demand for pepper will: "escalate colossally to about 280,000 metric tons by the year 2020, which will further climb to 360,000 metric tons by 2050."

Together with a number of other spices, it has been suggested that pepper helps to improve the taste, aroma, and flavour of food (Korikanthimath, 2003; Peryam and Swarty, 1951). According to one intriguing recent suggestion, piperine, the key trigeminal stimulant in black pepper, may affect the perception of saltiness (Moss et al., 2023a, 2023b). As such, black pepper, specifically piperine, might be

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[1] Cardamom is referred to as the 'queen of spices' (Nair, 2011).

[2] Note that although the chile pepper may be the world's most used spice, its value in the spice trade is not high because it has rarely been traded over long distances (Spence, 2018b; Wright, 2007).

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considered to function as something of a taste/flavour enhancer (see McNamara et al., 2005). It is also known and used for its functional properties (Nisha et al., 2009; Suresh et al., 2007). It should, though, be noted that the culinary and medicinal (anti-microbial, anti-bacterial, and antioxidant) virtues of pepper tend to be associated with different constituents, such as the alkaloid piperine, volatile compounds of the essential oil, polyphenols, and carotenoids (Agbor et al., 2006; Gulçin, 2005; Karsha and Lakshmi, 2010; Nikolić et al., 2017). The addition of spices such as pepper may help to preserve foods due to their antimicrobial properties (e.g., Sherman and Billing, 1999; Sherman and Flaxman, 2001; Sherman and Hash, 2001; see also Nakatani et al., 1986). Contemporary statistical analyses have, though, argued against the antimicrobial hypothesis as an explanation for the variation in spice use in different countries/regions (e.g., see Bromham et al., 2021; Zhu et al., 2013). The essential oil extracted from black pepper fruits has been shown to exhibit a myriad of biological activities (e.g., Haq et al., 2021). Indeed, black pepper (*Piper nigrum*) has been extensively studied scientifically (e.g., Govindarajan and Stahl, 1977; Jayashree et al., 2009; Menon and Padmakumari, 2005a, b; Kato and Furlan, 2007; Parmar et al., 1997; Siddiqui et al., 2005; Zachariah et al., 2010). Nowadays, pepper has extensive culinary uses in terms of flavouring and helping to preserve processed foods; it is also used medicinally.

1.1. Why do we find black pepper on the dinner table?

One intriguing (albeit difficult to definitively answer) question concerns why it should be that people have chosen to put pepper on the table over the centuries (cf. Andrews, 1999, pp. 29–33). Or, as Jacewicz (2018) puts it: "How did salt and pepper become the mainstays of Western cuisine?" Why not chile, or nutmeg, cinnamon or, in fact, any of the other herbs, one might ask.[3] Though, as Ken Albala points out, it hasn't always been there. In Europe during the Late Middle Ages, "Pepper was never on the table, nor was any other spice, for that matter. Usually spice would be added in the kitchen with a very heavy hand until the 17th century" (as quoted in Jacewicz, 2018; cf. Viestad, 2022). Table-top seasonings (and condiments; see Hazlitt, 1902; Spence, 2018a) presumably allow room for people to satisfy their own personal preferences and taste idiosyncrasies (Jacewicz, 2018), something that is especially important given that we live in such different 'taste worlds' (Bartoshuk, 1980). At the same time, however, individual differences have been documented in the perception of bitterness from piperine (Green and Hayes, 2004). That being said, not all chefs necessarily appreciate their guests modifying the taste of the food they serve. For instance, Spence (2017) highlighted how the chefs at several high-end London restaurants had deliberately removed the salt and pepper from the table in order to deny their guests the opportunity to modify the chef's culinary intentions.[4] Nevertheless, notwithstanding such idiosyncratic exceptions, the ubiquity of black, and to a lesser extent white, pepper on dining tables around the globe, when taken together the flavour-enhancing qualities (in the absence of any negative health effects), means that this spice would appear to be ideally placed to help consumers to healthily add flavour to the food they eat.

1.2. Pepper production

Pepper is one of the oldest and most extensively used spices and traditional medicines known to humankind. Black pepper is obtained from the fruits of *Piper nigrum* L., a perennial woody evergreen climber, native to the evergreen forests of the Western Ghats of South India. The genus Piper (*Piperaceae*) is represented by about 1500–2000 species of perennial evergreen climbing, lianescent herbs or shrubs distributed in both tropical and sub-tropical regions. The plant is thought to have originated in India and Indonesia. According to Ravindran and Kalluparackal (2000, p. 62), South West India is the traditional home of this spice, particularly the Western coastal regions of South Peninsular India (namely the Malabar Coast). Nowadays, however, pepper is such a commercially-important commodity that it is cultivated throughout tropical regions/zones around the world, including in India, Brazil, Indonesia, Malaysia, Vietnam, Sri Lanka, Thailand, China, Brazil, Mexico, Guatemala, and Cambodia (Lawless, 1989; Ravindran and Kalluparackal, 2000). Currently, pepper is produced in about 26 countries. Around the turn of the century, the total global area under pepper production was around 404,000 ha producing around 180,000 tonnes of pepper annually. In 2017, 690,000 tons were produced, with 32% supplied by Vietnam, at the time the leading producer ahead of Indonesia and India (FAO Statistics Division, FAOSTAT, 2019; Sawe, 2019). According to Sawe, as of 2019, Vietnam, Indonesia, India, and Brazil were the top four producers of black pepper, collectively accounting about 72% of global black pepper production.

In this narrative historical review, the literature on the chemistry, psychology, history and gastronomy of pepper (and its use) are critically reviewed (see Ferrari, 2015; Furley and Goldschmied, 2021, on the strengths of narrative historical reviews). One of the key suggestions to emerge from this review concerns the psychological impact that allowing consumers to add pepper at the table may have in terms of the consumer's enjoyment of the flavour of those foods to which this spice has been added. The psychological/cultural aspects os spice use are thus foregrounded rather than the merely chemical analysis of the compounds contained within the various peppers as a function of their preparation.

2. Popular pepper varieties

Although several species are domesticated today, *Piper nigrum* accounts for the overwhelming majority of global pepper production. White, green, and black peppers are products of the *P. nigrum* fruits at different stages of ripening (Buckle et al., 1985). By far and away the largest use is of black pepper which is collected once the fruit has reached full maturity but before it is fully ripe. The peppercorns are briefly boiled in hot water to accelerate the activity of browning enzymes during drying (Milenković and Stanojević, 2021). It has a stronger flavour compared to white pepper while green pepper, which is less ripe fruit (Orav et al., 2004), is characterized by its fresh and herbal flavour. White pepper is prepared from the fully ripe fruits by removing the outer pericarp prior to drying. White pepper powder is made by peeling, soaking and blanching the fully-ripened fruit. White pepper is thus the interior meat of the fully ripened corn with the hulls removed by soaking and rubbing (Lawless, 1989).

White pepper is primarily used in those foods where the dark particles of black pepper would be undesirable, such as salad dressings, soups, chowders, mayonnaise, light coloured sauces, etc. (Fincher, 2020). Perhaps unsurprisingly, white and black pepper impart a somewhat distinct flavour to foods. So, for example, according to Fincher, black pepper gives off more of a spicy heat (due to the presence of piperine), whereas white pepper's flavour tend to be more earthy and musty (cf. Steinhaus and Schieberle, 2005).[5] However, I have yet to come across the relevant flavour chemistry analysis (e.g., using GC/MS) directly comparing the two types of pepper (though see Friedman et al.,

[3] The chile pepper was obviously at something of a disadvantage given that it was only introduced to western cuisine following the 'discovery' of the New World a little over 500 years ago (see Pennell, 2010; Wright, 2007).

[4] Marco Pierre White, the first British celebrity chef to be awarded three Michelin stars, was once famed for throwing diners out of his restaurant should they ask for the salt and pepper. White considered it an insult for any diner to want to season their food in his restaurant (White, 1990).

[5] Fincher writes that: "Because the skin is removed, some of the flavor is taken, including the piperine. As a result, white pepper tends to be more mild than black pepper."

2008, for a comparison of various piperamides, pungent bioactive alkaloids, in black, white, red, and green peppercorns and ground pepper; and see also Jagella and Grosch, 1999b, c). Red and green peppercorns are sometimes also used in cuisine (Bandyopadhayay et al., 1990) (see Table 1). Green peppercorns are a staple ingredient in Thai cuisine, as well as in the cooking of a number of other Eastern and South Eastern Asian countries. Green peppercorns tend to be highly aromatic, fresh tasting, and have only a mild black pepper flavour.

In recent years, a number of more unusual varieties of pepper, such as the wild *Tsiperifery* pepper (*Piper* spp.) from Madagascar have been 'discovered' (Weil et al., 2014). However, although the unique flavour properties offered by these unusual varieties have undoubtedly proved popular with a number of international chefs, including Anne-Sophie Pic and Wolfgang Puck, as well as chocolatiers such as Francois Pralus, it remains unclear whether this intriguing variety of pepper necessarily represents a commercially-viable proposition (see Trubeck et al., 2021, for a review). *Piper borbonense*, meanwhile, is another poorly-known wild pepper from Reunion island (Weil et al., 2020). The low pungency (piperine content, 0.2%) and high aroma potential (essential oil content, 9.8%) of the latter brings its flavour profile closer to that of some other tailed peppers such as *Piper cubeba* and the wild peppers of Madagascar, while at the same time setting it apart from *Piper nigrum* (Weil et al., 2020). At the same time, the presence of asaricin (13% in the essential oil) of *Piper borbonense,* also differentiates it from black pepper (where the concentration is typically <1%). Its aroma composition is very rich in monoterpenes, most notably limonene (27%).

Table 1
Some more or less common types of pepper. The genus Piper (*Piperaceae*) isrepresented by somewhere between 1500 and 2000 species (Milenković and Stanojević, 2021). Two genera, *Piper* (about 1000 plant species) and Peperomia, represent 90% of all species.

Pepper variety	Flavour attributes
Piper nigrum Linn.	
- Black peppercorns (mature but not fully ripe, i.e., red, fruit)	Spicy piquant heat, together with a fruity aroma (piney, citrusy, & fresh top note, with a pungent, herbaceous, woody, earthy, & spicy base note)
- White pepper (fully ripe and mature fruit with pericarp (hull) removed) prior to drying	More of an earthy, musty flavour that is milder than black pepper; contains more sabinene (13% essential oil); warm oily-peppery, woody, herbaceous and spicy aroma
- Green peppercorns (unripe fruit)	Fresh-tasting aromatic & herbal flavour
Piper longum Linn.	Traditionally popular variety; taste similar to, but hotter than, Piper nigrum
Piper betle Linn.	Leaves have a sweet to pungent taste
Piper cubeba Linn. f.	Aroma described as agreeable & aromatic; Taste is pungent, acrid, slightly bitter, & lingering
Piper chaba	Spicy and pungent
Piper retrofractum Vahl	Tastes similar to Indian long pepper (P. longum)
Pimenta dioica L. (Merrill) (Allspice) Jamaica pepper	A flavour that evokes a blend of nutmeg, cloves, and cinnamon
Piper guineense Schumach et Thonn, also known as Guinea pepper, Ashanti pepper, African black pepper)	Similar to cubeb pepper but is less bitter and has a fresher, more herbaceous flavour and aroma than cubeb's
Grains of Paradise (*Aframomum melegueta* [Roskoe] k. schum)	Complex flavor: woody, peppery, herby, with a warm subtle heat. Notes of ginger, citrus, cardamom, coriander, nutmeg, and juniper
Tsiperifery (from Madagascar)	Woody, fruity, flowery smell and taste
Piper borbonense (from Reunion island)	Low pungency, highly aromatic (limonene - c. 27% of essential oil, and asaricin - 13%)
Szechuan peppercorns (berries of the ash tree)	Delivers an orange flavour with tingling chemesthetic shagoal
Pink peppercorns (from Brazilian pepper tree *Schinus terebinthifolius*)	Sweet aroma/flavour w. Notes of fresh pine and citrus
Zanthoxylum piperatum DC tree (also known as Japanese pepper)	Black, aromatic and pungent fruit belonging to the Rutaceae family

Pink peppercorns are the fruit of Brazilian pepper tree *Schinus terebinthifolius* (Barbosa et al., 2007; McGee, 1984/2004, pp. 427–428; Tlili et al., 2018).[6] Guinea pepper (*Piper guineense* Schumach et Thonn), meanwhile, is generally referred to as African black pepper or Ashanti pepper (Adefegha et al., 2017). Grains of paradise (a pungent West African plant, *Aframomum melegueta* [Roskoe] K. Schum.; Barton, 2021; Wright, 2007), while once popular in medicinal and culinary recipes, was heavily taxed by the British Government, leading to its virtual disappearance by 1827 (Hepper, 1967). There are also Szechuan peppercorns, which are not part of the pepper family, but are actually the berries of the ash tree (see June, 2021).[7] Other species of pepper that are less common, but which are nevertheless still grown and consumed today, include *Piper cubeba* (Bos et al., 2007; Buckle et al., 1985) and *Piper longum* (e.g., Varughese et al., 2016). The latter variety originates from northern India, whereas *Piper nigrum* originated from the south of the country (Parker, 2002; Zachariah and Parthasarathy, 2008).[8] Long pepper, spikenard, or *pippali*, is more piquant than black pepper (Babu et al., 2006; Mamatha et al., 2008). However, by the 15th and 16th centuries it was only a minor crop (Hyman and Hyman, 1980; Matthews, 2015); though it does appear in Thomas Newbery's (1563). *A booke of Englysh metre, of the great marchaunt man called "Dives Pragmaticus'*. Long pepper traditionally arrived in Europe via overland trade routes from northern India, while pepper came via sea routes (Matthews, 2015). Matthews also writes that "Long pepper is believed to have been the first of the peppers to reach the Mediterranean. And, throughout antiquity, it was more highly regarded than black pepper. In ancient Rome, it was a luxury item that cost twice as much as black pepper. As in India, long pepper was used primarily for its medicinal properties, though it was also used to flavour food and wine." Other spices which are called "pepper,' belong to different genera, such the members of the genus *Capsicum*, that including cayenne, chili, red, and bell peppers. The black, aromatic and pungent fruit of the tree *Zanthoxylum piperatum* DC which belongs to the family *Rutaceae* is known as Japanese pepper (Govindarajan & Stahl, 1977).

2.1. Medicinal (and other non-culinary) uses for pepper

Historically, pepper has often been used medicinally (e.g., George, 1995), for example, as a carminative or febrifuge, to aid digestion, and in curing the common cold (Ravindran and Kalluparackal, 2000). Piperine has also been reported to have a blood pressure lowering and vasomodulatory effect (Taqvi et al., 2008). Interestingly, a wide range of contemporary research supports pepper's anti-microbial, anti-oxidant, anti-inflammatory, and other health-related properties (e.g., Ahmad et al., 2012; Bai and Xu, 2000; Butt et al., 2013; Choi and Hwang, 2003; Lai et al., 2012; Lee et al., 1984; Milenković and Stanojević, 2021; Rameshkumar et al., 2011; Singh et al., 2013; Srinivasan, 2008; Sunila and Kuttan, 2004; Zarai et al., 2013; see Wu et al., 2009, for a summary of research from China). Pepper may also possess analgesic properties (Costa et al., 2016), and it has even been suggested that it might act as an anti-depressant (Butt et al., 2013; Khan, 2015). At the same time, it may also help in the treatment of disorders of the airways, due to its ability to cause bronchodilation (Rehman et al., 2015).

[6] It has been suggested that pink peppercorns have a sweet aroma/flavour with aroma notes of fresh pine and citrus thanks to the presence of several terpenes (McGee, 1984/2004, pp. 427–428).

[7] Consider here also peppermint (*Mentha piperita*), a peppery variety of mint (Jordt et al., 2003; Onstad, 1996).

[8] In fact, it was why the chile pepper was so-named, as that was what Columbus was searching for on his trip to the New World (see Spence, 2018b, for a review). In the explorer's defence though, it is worth noting that the traditionally more popular long pepper (Laskow, 2016) looks quite similar to the chile pepper (and certainly much more similar than to the processed black peppercorns that are more familiar to us today).

Pepper oil also plays an important role in perfumery (Lewis et al., 1969). According to Indian folklore it was traditionally considered something of an aphrodisiac (Nadkarni, 1982, pp. 969–972). Black pepper extract may also have an insecticidal function (Rehman et al., 2015; Szallasi, 2005; Weluwanarak et al., 2023).

3. On the longstanding historic popularity of pepper

As has been noted already, pepper's popularity as a culinary ingredient stretches back thousands of years. Archaeological evidence for its domestic use as a condiment at table is provided by silver pepper shakers (*piperatoria*) found in various parts of Italy (Simmons, 2021; Strong, 1966, p. 154, pp. 178–180), though these would likely have been handled by slaves (Simmons, 2021, p. 323).[9] Pepper has long been added both in the kitchen and at the dining table. Indeed, evidence supporting the latter suggestion comes from a number of ornate pepper dispensers that were brought to Britain at end of Roman occupation (cf. Nicolet 1991) (see Fig. 1).[10] One reason to add herbs and spices at the end of cooking (or else at the table), is if they might degrade, or lose their flavour/anti-microbial function if added earlier, as in the case parsley and coriander leaf (see Nisha et al., 2009; Suresh et al., 2007). This would not, however, seem to be the case for pepper.

3.1. Pepper's popularity in ancient Rome

Pepper was one of the luxuries that was imported into Ancient Rome from India (Parker, 2002). The Roman Empire consumed huge amounts of pepper (Cobb, 2018). The popular spice played an important role medicinally as well as in a religious context (Simmons, 2020). Pepper appears in the majority of the recipes in Apicius's fourth century cookbook (Apicius, 1936), though it is somewhat unclear whether what is being referred to is actually clove or nutmeg or a mixture of different spices (see Barton, 2021). One finds fictional historic mention of the freed slave Trimalchio using large/excessive amounts of pepper to flaunt his newfound wealth (Parker, 2002). In Ancient Roman times, pepper was a highly desirable spice that was nevertheless somewhat unusual in that it had to be imported from outside the empire (namely from India, Mayer, 2018; Parker, 2002). In Ancient Rome, pepper served the function of a Veblen good, providing a means for the ostentatious display of luxury (Veblen, 1899/1992; Viestad, 2022). According to Pliny, black pepper sold at 15 denarii per pound in Rome (Miller 1969; Simmons, 2021). That said, not everyone was a fan. Pliny the Elder queried why it should be that so many Romans would pay so much for something that delivered nothing but pungency (Banducci, 2018; Rudolph, 2018).[11] White pepper, meanwhile, which has a milder taste/flavour, was more often used as a medicine (i.e., rather than as a culinary spice) in Roman times.

3.2. Pepper's use in the Middle Ages and beyond

According to Whittet (1968), the first known record of pepperers operating in Britain appears in the Pipe Roll of 1180, as the Gilda 'Piperarorium'. So important was this spice that those who handled spices wholesale became known as 'pepperers'. The 'spicers' would deal with retail sales, and apothecaries mainly dealt in medicines. Alexander Neckham, in his 12th Century *De Utensibilis* [Treatise on Kitchen Utensils], mentions the use of a pepper-mill in the kitchen (as cited in Hazlitt, 1902). See Wake (1979) for further information on the changing patterns of Europe's pepper and spice imports, ca. 1400–1700.[12] Pepper was a hugely popular spice, though prices dropped dramatically during the 15th Century before rising once again, as a result of changes in international trade and navigation (see Lane, 1968).[13] "When Vasco de Gama sailed for India in 1497, the annual imports of black pepper to Europe were about two million pounds; by 1506 that figure had risen to about three million pounds, and in 1570, to about six million pounds" (Wright, 2007, pp. 36, 35, 39). It has been estimated that the English were importing around 1.2 million kilograms of pepper during the first half of the seventeenth century. By 1872, statistical records reveal imports of 12.6 million kilograms, although almost 3.8 million kilograms were re-exported to continental Europe (Fliickiger and Hanbury 1874, p. 523; Furber, 1976, p. 236). Freedman (2012, 2015) has also written extensively on the role and uses of luxurious spices such as pepper in the Middle Ages and Medieval Period.

According to Smith (2007), pepper was also added to desserts such as *potage appele verzuse,* and stewed with fruit into *confitures*. However, attitudes toward the use of pungent pepper started to change in Mediterranean countries where the 'black devil' began to be scorned in favour of Spanish pimento, or chili pepper, where needed (e.g., Durante, 1585, p. 344). According to Alexandre Dumas (1802–70), writing about nineteenth-century country fare, pepper was 'a rude' *(grossiere)* spice (Dumas, 2000, p. 452; see also Mercier, 1782–3). Abbe Raynal (1777) equated such spices with barbarian gluttony and a cult of excess (see Braudel, 1973). (This a marked change from when the phrase 'a peppercorn rent' had first been introduced in England.)

Considering the historic use of pepper in Britain, one finds 24 mentions of pepper (Hazlitt, 1902) though several of those refer to Jamaica pepper (i.e., pimento, or allspice).[14] Meanwhile, there are more than 660 mentions of pepper, often together with salt, in Isabella Beeton's Household management (Beeton, 1861). As has been mentioned already, global sales of pepper have continued to rise year-on-year (Anonymous, 2008, p. 3; Nair, 2020). Part of pepper's continued popularity comes from its various novel culinary uses, e.g., in ice-cream, chocolate, etc. (e.g., Aumpa et al., 2022). However, the fact that pepper is primarily associated with savoury foods, unlike in former times when it would also have been used in a wide variety of desserts and drinks, is also worth noting. Looking back over time, Andrews (1984) suggests that the incorporation of spices (specifically domesticated capsicums) is linked to those diets having a high cereal density. Indeed, when compared to salt, sugar, or fat, spices such as black pepper and chile pepper appear to deliver both culinary (i.e., in terms of flavouring), preservative (i.e., anti-microbial and anti-bacterial), and health-related benefits.

[9] Such evidence obviously contradicting the claim that is sometimes expressed that the tall pepper grinder might have been a modern invention associated with the Italian restaurant.

[10] The *Fairfax inventories* (1594–1624), edited by Peacock, assert that a pepper mill is an important kitchen utensil (again cited in Hazlitt, 1902).

[11] At one point, Pliny the Elder asks: 'Why do we like it so much? Some foods attract by sweetness, some by their appearance, but neither the pod [long pepper] nor the berry of pepper [black pepper] has anything to be said for it. We only want it for its bite - and we will go to India to get it!' (Matthews, 2015; see also Eichholz et al., 1949–1954).

[12] "The old English saying 'He hath no pepper' describes people who are 'nobodies'." (Smith, 2007, p. 237).

[13] As part of what has been described as the Columbian Exchange (Crosby Jr., 1973), the pungent capsicum, allspice, and vanilla were introduced into the Old World, while pepper, cardamom, and ginger from the East were introduced into the Americas (Govindarajan and Stahl, 1977). Trubeck et al. (2021, p. 347) summarize the global spice trade thus: "The global spice trade defines the modern human experience, past, present, and future. The desire for the tastes provided by them … have propelled civilizations, justified colonialism, inspired plantation production systems, precipitated complex trade networks and concomitant trade conflicts, expanded cuisines, transformed sensory experiences and on and on."

[14] Jamaican pepper is made from the dried and processed berries of an evergreen tree, *Pimento dioica* L. (Merrill), native to the West Indies and tropical America.

Fig. 1. The 'Empress' pepper pot (silver), found as part of a large hoard, buried in the early fifth century AD, at Hoxne in Suffolk, Britain (see Johns, 2010): (a) full view; (b) base showing a disc which could be turned to three positions: one closed, one with large openings to enable the pot to be filled with ground pepper, and a third which revealed groups of small holes for sprinkling. © Trustees of the British Museum.

3.3. Does it matter who adds the pepper?

Intriguingly, in one recent study, the participants (n = 76) evaluated a low-sodium soup to which white pepper had been added (at detection threshold) using hedonic scales, general Labelled Magnitude Scale (gLMS) for saltiness, check-all-that-apply (CATA), and temporal check-all-that-apply (TCATA). The results indicated that the saltiness intensity increased with the addition of white pepper based on the results of the gLMS; however, this result was not confirmed using CATA or TCATA. Rather peppery, bitterness, sourness, and strong aftertaste attributes dominated the participants' perception of the soup. Surprisingly, the addition of white pepper actually decreased the participants' overall liking of the soup as well as their liking of its flavour and texture. Future research should therefore continue to investigate the crossmodal interactions of white pepper (Moss et al., 2023b). Here, one might wonder whether this surprising result (in terms of the taste/flavour consequences of adding white pepper) might speak to the importance of whether the pepper happens to be added by the consumer or not, given the 'IKEA effect' (Norton et al., 2012; Spence, 2017). The latter is the name given to the observation that consumers appear to rate those foods that they have had a hand in making as tasting better than those foods that they believe have been made by someone else.

4. Pepper's multisensory contribution to flavour perception

Black pepper stimulates several senses simultaneously – taste (gustation), the trigeminal nerve (or chemesthesis), and olfaction (thus contributing to flavour; Narayanan, 2000; Tausig et al., 1956; Yang et al., 2016). While black pepper can deliver a desirable fruity aroma to food, its pungency, typically described as stimulating the trigeminal system (Viana, 2011; though see also Green, 1996), has always been key to pepper's culinary/consumer appeal. Although the trigeminal nerve is also responsible for touch, heat, cold, and pain in mouth, Lawless argues that the pepper sensation cannot be classed as a form of oral-somatosensation. The trigeminal system has often been overlooked (and pungency has even been called the forgotten flavour sense by Lawless, 1989), despite the popularity of various foods that possess astringent or irritant properties. Rather than stimulating taste buds, the heat of pepper results from the stimulation of the trigeminal nerve endings, which are distinct from the nerve that makes contact with the taste buds. The trigeminal sense organs in the nose are also distinct from these (Silver and Maruniak, 1981). However, as Lawless (1989) notes, the sensory reaction to pungent pepper compounds is not really a thermal sensation, even though people use the term 'hot' to describe it. It is more accurately classified as a chemically-induced form of irritation, one that is different from both taste and touch.

Piperine is the flavour component responsible for the 'hotness' of both white and black pepper (Govindarajan, 1977; Lawless, 1989). Piperine is the major pungent constituent of pepper oleoresin (Borges and Pino, 1993). However, pepper also contains a number of volatile components that are important as far as aroma/flavour is concerned (Govindarajan, 1977; Narasimhan et al., 1990). According to McGee (1984/2004, p. 427), the major compounds that are responsible for the flavour of black pepper are piperine (2–9%; Gorgani et al., 2017), and volatile aromatic compounds (2.4–3.8%; Lewis et al., 1969; Russel and Else, 1973) (see Table 2). However, the exact composition of black pepper essential oil depends upon the variety, or cultivar, tested (Martins et al., 1998; Nisha et al., 2009; see also Joy et al., 2011), as well as storage conditions, and country of origin (Liang et al., 2021; Zhang et al., 2015). So, for example, Narasimhan et al. (1990) demonstrated that the sensory quality of powdered black pepper deteriorated significantly during a 15 day storage period due to the loss of volatile components. By contrast, the piperine content remained stable for the

Table 2
Some of the main chemical constituents of black pepper fruit (Figures taken from Gorgani et al., 2017; See also Milenković and Stanojević, 2021.).

Constituent	Percentage
Piperine	2–9%
Oleoresin	4–12%
Essential oil	0–7%
Starch	50%
Fatty oils (acids)	2–9%

80-days over which it was assessed. Whole white peppercorns retain their flavour for around three years, while ground white pepper lasts for something like three months (Fincher, 2020).

4.1. Pungent piperine

The alkaloid piperine (c. 1.7–7.4%, depending on the plant) gives rise to the pungency of black pepper (Kanaki et al., 2008; Narasimhan and Rajalakshmi, 1981; Schulz et al., 2005; Srinivasan, 2007). The threshold for the detection of piperine is 0.55 ± 0.15 ppm (Moss et al., 2023a), meaning that it can be detected in concentrations of as little as 20 parts per million (or just 20 mg in a litre of water; see Lawless, 1989). Capsaicin, the active compound of red pepper is though about 100 times more potent (Govindarajan, 1979, p. 53). However, neither ingredient is particularly water soluble, and thus requires emulsification, or the presence of oil-based solutions, in order to effectively flavour the food to which it is added.

Cautioning against referring to the pungency of black pepper as simply a trigeminal stimulant, Green (1996) notes that the sensation of pungency appears to come from those regions of the oral cavity that are simply not innervated by the trigeminal nerve, i.e., such as the anterior oral cavity; cf. Cliff and Heymann (1992). Note here that pharyngeal sites (i.e., the oral pharynx and throat) are innervated by glossopharyngeal (IX) and vagus (X) nerves, but not by the trigeminal nerve (Brodal, 1972; Spence, 2022b). Importantly, research from Rentmeister-Bryant and Green (1997) found that the oral irritation from piperine (and capsaicin) was at least as strong in the posterior regions of the oral cavity. These researchers assessed the perceived irritation in the oropharyngeal region when their participants ingested capsaicin and piperine. The participants rated four qualities of the ensuing stimulation: Location (anterior tongue, posterior tongue, roof of mouth, and throat), pungent (burning, tingling, numbing, and overall), temporal qualities (lag time, overall duration), and spatial qualities (longitudinal location, lateral location, and localized/diffused). Piperine primarily gave rise to a burning sensation of long duration, with a slight tingling numbing that was reasonably uniform along the rostro-caudal axis, with throat ratings being similar to those of the anterior tongue (cf. Beltrán et al., 2017). If anything, the pungency of piperine (in solution) was experienced more towards the front of the tongue, with a lag described as modest, and of medium duration. According to Green (1996), it may be more appropriate to describe pepper's pungency in terms of the stimulation of the common chemical sense (Silver, 1987), or as a form of chemesthesis, rather than necessarily as a straightforwardly trigeminal stimulant (see also Lawless and Stevens, 1984, 1988; Rentmeister-Bryant and Green, 1997).

Piperine is often described as tasteless straight after ingestion. However, this initial impression is subsequently replaced by a recognisable sharp, peppery, 'burning' aftertaste. Piperine (1-peperoylpiperidine), is the primary alkaloid that gives black pepper its pungency, activating the human vanilloid receptor (TRPV1; McNamara et al., 2005).[15] Many naturally occurring pungent compounds (and spices) have now been shown to activate this heat and capsaicin receptor, including the ginger extracts zingerone and gingerol, nutmeg and clove oil constituent eugenol (see also Okumura et al., 2010).

Although black peppercorns are rich in vitamins A and K in addition to dietary fibre, calcium, magnesium, potassium, manganese, phosphorous, and β-carotene (Butt et al., 2013; Meghwal and Goswami, 2012), it seems unlikely that the presence of these micronutrients has played any significant role in the enduring popularity of this spice over the course of human history.

4.2. Volatile aromatic compounds

According to Narasimhan et al. (1990), black pepper has piney, citrusy and fresh 'top notes', together with pungent, herbaceous, woody, earthy and spice 'base notes'. Meanwhile, Schulz et al. (2005) suggest that the optimum pepper aroma ("top-peppery-note") is obtained if the monoterpene (excluding α- and β-pinene) content is high but at the same time, the pinene content is low. Gas-chromatography-mass spectrometry (GC/MS) has helped to establish the presence of the following key volatiles: Germacrene D (11%), limonene (10%), β-pinene (10%), α-phellandrene (9%), β-caryophyllene (7%), α-pinene (6%) and *cis*-β-ocimene (3%) (Jirovetz et al., 2002) (see Table 3). At the same time, however, olfactometry revealed that mono- and sesquiterpenes were essential contributors to the fine, pleasant aroma of black pepper, along with pinene and limonene. The major components of the essential oils were α-pinene, sabinene, δ-3-carene, limonene, β-caryophyllene, and α-humulene, as well as minor constituents such as δ-carene, β-phellandrene, isoborneol, α-guaiene, sarisan, elemicin, calamenene, caryophyllene alcohol, isoelemicin, T-muurolol, cubenol and bulnesol, are apparently of great importance for the characteristic aroma of black pepper (Jirovetz et al., 2002). The 'pepper' compound rotundone,[16] an obscure sesquiterpene, is sometimes expressed naturally in Australian Shiraz and Northern Rhône Syrah wines (e.g., see Bramley et al., 2016; Siebert et al., 2008; Wood et al., 2008). This compound is also found in small quantities in pepper.

According to Jagella and Grosch (1999a, b, c), (+)-linalool, (+)-α-phellandrene, (−)-limonene, myrcene, (−)-α pinene, 3-methylbutanol and methyl propanol are some of the most potent odorants of black pepper cultivars by GC-MS, electronic nose, and sensory analysis techniques (Mamatha et al., 2008). Analysis of the essential oils of black pepper using GC-MS have revealed that they were dominated by monoterpene hydrocarbons. GC-MS analysis reported by Singh et al. (2013) suggested that white pepper, like black pepper, contains β-caryophyllene (13%), and limonene (12%). However, it also contains

Table 3
Some of the key volatiles in essential oil of black pepper as reported by Jirovetz et al. (2002; cf. Milenković and Stanojević, 2021). It is, however, important to note that how these volatile essential oils smell when combined is difficult to predict (cf. Jagella and Grosch, 1999a, b, c; Meghwal and Goswami, 2012). One of the interesting omissions here is rotundone, a peppery sesquiterpene, that gives certain wines their freshly-cracked peppery nose, and is also present in small quantities in pepper.

Volatile	% of essential oil	Typical odour/flavour descriptor
Germacrene D	11%	Woody aroma
Limonene	up to 21%	Pleasant, lemon-orange citrus smell
β-pinene	up to 10%	Woody-green, pine-like smell
α-phellandrene	9%	Herbaceous, woody, minty, and mildly citrus aroma
β-caryophyllene	up to 30%	Warm, woody, spicy and peppery aroma
α-pinene	up to 6%	Pine scent, earthy, and woody with hints of turpentine
cis-β-ocimene	3%	Warm, floral, sweet odour
Myrcene	<1%	Earthy, fruity, and clove-like aroma
p-cymene	1–8%	Harsh chemical, woody and terpy-like with an oxidized citrus lemon top note (Govindarajan, 1977; Mamatha et al., 2008)
Sabinene	up to 11%	Warm, oily-peppery, woody-herbaceous and spicy odour
(+)-linalool	<1%	Floral, citric, fresh and sweet aroma (Jagella and Grosch, 1999a,b, c)

[15] This has been described as an exquisite molecular integrator of multiple chemical and physical stimuli to which the receptor is exposed.

[16] The compound rotundone, with its characteristic "black pepper" aroma, was first isolated from the grassy weed *Cyperus rotundus* L. by Kapadia et al. (1967).

sabinene (13%), described as having a warm, oily-peppery, woody-herbaceous and spicy odour, torreyol (9%), and β-bisabolene (7%), which has a balsamic odour. Ultimately, of course, any difference between white and black pepper flavour characteristics must relate to the effects of ripening, and the chemical contents of the pericarp.

4.3. Varietal differences in pepper

Black pepper oils from various geographical locations exhibit qualitative similarities as well as differences in the concentrations of their major volatile components. β-Caryophyllene, limonene, β-pinene, α-pinene, δ-3-carene, sabinene, and myrcene are the main components of *P. nigrum* oil, with cluster analysis revealing four clearly defined clusters (Dosoky et al., 2019). Different cultivars of *Piper nigrum* express somewhat different flavour profiles, while the oil content may also vary (e.g., Lewis et al., 1969; Richard et al., 1971; Russel and Else, 1973; Salehi et al., 2019). Some cultivars of pepper (e.g., Balankotta) have even been reported to deliver green-mango-like, tumeric-like and earthy notes (Mamatha et al., 2008). Some of the key aroma/flavour volatiles of four varieties of black pepper included peppery, citrus/lemon-like, fresh green, camphoraceous, sharp/pungent, warm and spicy, woody/resinous, dried herb, turmeric-like, refreshing/pine-like (see Gopalakrishnan et al., 1993). Meanwhile, Liu et al. (2013) reported studies on the chemical and flavour qualities of white pepper (*Piper nigrum* L.) derived from five new genotypes. Researchers have also conducted comparative GC-MS analysis of the essential oils of *Piper nigrum* L. and *Piper longum* L. (see Liu et al., 2007).

It is, though, important to recognize that the way in which individual volatiles will be perceived when they are combined can be hard to predict (Mamatha et al., 2008). At the same time, possible differences between the orthonasal and retronasal perception of specific odorants should not be neglected either (Rozin, 1982). The age of the peppercorns, and whether or not they have been freshly ground (and hence the length of storage; Narasimhan et al., 1990), not to mention whether the pepper happens to be dissolved in a water-, fat-, or starch-based medium can all impact the final flavour profile (Mamatha et al., 2008; Pangborn et al., 1970). At the same time, however, it should be noted that it can sometimes be difficult to predict exactly how different components will interact to influence taste/flavour perception (Liu et al., 2021; Moss et al., 2023a, b; Rosin and Tuorila, 1992; Utama-ang et al., 2020).

While pepper samples are sometimes evaluated in isolation, this is a rather strange (i.e., ecologically-invalid) tasting experience (see Potts, 2023), given that pepper is nearly always added to season other foods (i.e., rather than the taste of peppercorns being savoured in their own right). As Olivia Potts (2023, p. 40) puts it of her time assessing the aroma, texture and colour of peppercorns for the food award industry: "What should a peppercorn taste like? … But could I differentiate between a good peppercorn and a really great one? Tasting, in isolation, something that I would realistically only ever eat in combination with other ingredients felt a little artificial." Looking back over time, Andrews (1984) suggests that the incorporation of spices (specifically domesticated capsicums) is linked to those diets having a high cereal density. Indeed, when compared to salt, sugar, or fat, spices such as black pepper and chile pepper appear to deliver both culinary (i.e., in terms of flavouring), preservative (i.e., anti-microbial and anti-bacterial), and health-related benefits.

4.4. Pepper adulteration

Given its popularity, and hence expense, at many points in our history (Singh, 2015), it should perhaps not come as any surprise to find that pepper has often been adulterated (e.g., Bauer, 2021; Hemphill, 2021; Li et al., 2018; Parker, 2002). Nowadays, though, increasingly sophisticated methods have been developed in order to assess the quality of this spice (Bhattacharjee et al., 2003; Toledo-Martín et al., 2016). That said, there are also still many gaps in our knowledge as underlined by the fact that it is apparently still not possible to reliably distinguish between the various different species of pepper by means of chemical analysis (Weil et al., 2021; though see also Barata et al., 2021). Such an observation may not, however, be so surprising once it is realised that the genus Piper (*Piperaceae*) numbers somewhere in the region of 2000 species worldwide (Milenković and Stanojević, 2021), of which only around 550 have so far been described (Jaramillo and Manos, 2001).[17]

5. Conclusions

Black (and to a lesser degree white) pepper has long been one of the most popular spices in Europe and elsewhere (see Spence, 2021, for a review). It remains both popular and also relatively unique as the principal spice that is found on many dining and restaurant tables around the world. Pepper has been shown to possess a range of anti-microbial and anti-oxidant properties, as well as a range of other putative health benefits. Given growing concerns about the negative consequences of people's over-consumption of salt (e.g., Pavia, 2015), one (salt-reduction) strategy that has been suggested involves the mineral's gradual replacement by the increased use of flavour enhancers that contain less salt, such as monosodium glutamate (Spence, 2022a), chilli pepper (Spence, 2018b; Spencer and Dalton, 2020), garlic (Spence, 2024a), and perhaps also black pepper (Ghawi et al., 2014).[18] Ultimately, though, it would appear that black pepper's position on the dining table reflects its former status as a luxury product (Veblen good; Cobb, 2018), rather than necessarily because of anything specific about its flavour profile, or flavour-enhancing properties even though, as we have seen, the research suggests that it may be something of an effective flavour-enhancer.

Looking to the future, the fact that pepper is already found on many dining tables around the world, together with the fact that it delivers a pungent boost to the flavour of food would appear to make it ideally placed as flavour enhancer (see Moss et al., 2023b, for the latest research along just these lines), one that also allows the consumer to personalize their own tasting experience. Crucially, thus far, pepper would appear to have avoided criticisms linked to the overuse of flavour enhancers such as monosodium glutamate (MSG) and kokumi in our processed and ultra-processed foods (see Schatzker, 2016; Van Tullen 2023). The only fly in the ointment here comes from those high end chefs who seem to begrudge their guests' interfering with the seasoning of the dishes they create (Spence, 2017; White, 1990). At the same time, one also needs to bear in mind the possibility that the spice may taste better in food if added by the consumer rather than by the chef/food company (Norton et al., 2012; Spence, 2017).

Implications for gastronomy

Pepper (*Piper nigrum Linn.*) has long been one of the world's most popular spices. Along with the mineral, salt, it is one of the very few herbs and spices that plays a role both in the kitchen as an essential culinary ingredient as well as on the dining table as a condiment. Pepper stimulates multiple senses including taste, olfaction, and the common chemical senses (or chemesthesis). It may help to enhance the flavour of those foods to which it is added. Pepper conveys a number of health-related, preservative, and flavour functions in food, and may have an important role to play for those wishing to cut their salt consumption while not compromising on taste/flavour. Black, white, green, red, and

[17] Sumathykutty et al. (1999) suggest that there are around 700 species of pepper worldwide (see also Khan, 2015), while Ravindran and Kalluparackal (2000, p. 62) put the figure at about 1200 species.

[18] Lawless (1989) also suggests that the pungency of pepper may have a role to play in counteracting the effects of sensory loss relevant to flavour (e.g., in the elderly; see Spence, 2024b).

pink pepper, along with a range of other varieties (or species) of pepper each deliver a distinct flavour profile, varying in terms of the volatile aromas and peppery pungency of piperine, an alkaloid. Given that black (and to a lesser degree white) pepper is already found on many dining tables around the world, together with the fact that it delivers a pungent boost to the flavour of various dishes (primarily savoury, but on occasion also sweet), is would appear to be ideally placed as flavour enhancer (see Moss et al., 2023b, for the latest research along just these lines), one that also allows for the personalization of healthier food experiences.

CRediT authorship contribution statement

Charles Spence: Conceptualization, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

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

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