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Purple Tomato - Importance and Scope: A Review

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ABSTRACT

Fruits and vegetables are a rich sources of different nutrients, pigments, secondary metabolites and other nutritional components which are beneficial and fundamental components for human health. In recent years, the consumption of coloured fruits and vegetables has increased significantly due to their superior nutritional characteristics. In this context, purple tomato is now gaining importance due to the high content of the pigment anthocyanins. This article provides knowledge on 1) Tomato in general and anthocyanin-rich purple tomato, 2) Benefits of anthocyanins in plants and human diet, 3) Strategies for development of purple tomato, 4) Better postharvest life of purple tomatoes, 5) Purple tomato in India and 6) Health benefits of purple tomato. Purple tomato fruits provide higher nutraceutical value as compared to the classical red tomato as it combines the health benefits of the anthocyanins along with other usual and known phytochemicals as already present in tomato fruit. Due to higher anthocyanins and antioxidative properties, purple tomatoes possess anti-inflammatory, anti-microbial, anti-cancerous, cardio-protective, hepto-protective and neuroprotective effects. Regular consumption of purple tomatoes has also been found effective in the prevention of certain chronic diseases of humans as well. The use of conventional breeding and modern transgenic approach is paving the way for higher anthocyanin and other nutraceuticals in tomato fruits. Higher anthocyanin content has also imparted enhanced shelf-life and better storability to purple tomatoes. In the coming time, the availability and popularity of purple tomatoes in India will be beneficial for farmers, processing industries and human health. This will also serve as another step forward towards attaining nutritional security.

Key words: Anthocyanins, Anti-cancer, Anti-diabetic, Antioxidants, Health benefits, Purple tomato, Shelf-life.

The coloured fruits and vegetables have gained immense importance in recent times due to higher levels of pigments exhibiting antioxidative and nutritional values. Due to the nutritional value and high impact on humans in terms of providing food and nutritional security, UN General Assembly in Resolution A/RES/74/244 declared the year 2021 as an "International Year of Fruits and Vegetables (IYFV)". Moreover, the surge in the consumption of fruits and vegetables in the recent past indicates that they are becoming a part of the diet, in raw, processed, or value-added forms (Slavin and Lloyd, 2012). The coloured fruits and vegetables are not only beneficial in terms of human nutrition but the pigments are also involved in the regulation of ripening and senescence of fruits and vegetables as well (Paul *et al.,* 2005, Sharma, 2012, Sharma *et al.,* 2014). This aspect becomes more important for fruits like tomatoes because the process of fruit ripening and senescence is reported to be accompanied by an enhancement in the level of oxidative stress (rapid increase in the reactive oxygen species) (Jimenez *et al.,* 2002, Shibuya *et al.,* 2009, Paul *et al.,* 2011). The significance of the above can also be realized from the fact that the fast rate of tomato fruit ripening and decay due to pathogens and lack of proper, logistics and optimum conditions of postharvest storage contribute to huge postharvest losses for tomatoes (reaching up 25 to 40% or even more) (Paul and Pandey, 2009, Paul *et al.,* 2012, Paul and Pandey, 2018). All this emphasizes enhancement in the levels of different pigments with strong antioxidative properties in fruits and vegetables. This in turn will not only provide better nutrition and health benefits to humans but also better shelf-life and storability for tomatoes and other fruits and vegetables resulting in the overall improvement in postharvest management. So, researchers are now focusing on various ways to increase the levels of different health-promoting compounds in commonly consumed fruits and vegetables. The presence of anthocyanins in tomatoes (make them purple or purplish in colour) has gained much attention in the recent past because anthocyanin is absent in traditional varieties of tomatoes. This has been attempted not only from the point of view of protecting the fruits but also as a source of additional antioxidants along with other nutrition/nutraceuticals in the human diet. There are two ways to incorporate and improve the content of anthocyanins in tomato fruit that is by conventional breeding and modern transgenic approaches. This article is aimed to provide an updates on conventional tomato and anthocyanin-rich purple tomato, benefits of anthocyanins in plants and human diet, strategies for development of purple tomato, better postharvest-life of purple tomato, purple tomato in India, overall health benefits of purple tomato and lastly the future perspectives.

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Importance of tomato fruit

Tomato fruit is one of the most important vegetables across the globe which is consumed in raw form or after cooking (Paul and Pandey, 2013, Jangid and Dwivedi, 2016). Tomatoes are known for their obvious red colour. This red colour is due to the accumulation of a carotenoid pigment that is the lycopene in the flesh and peel of tomato fruit (Vela-Hinojosa *et al.,* 2019, Sharma *et al.,* 2020). Tomato fruit is a rich source of energy, carotenoids (lycopene, β-carotene and xanthophylls), flavonoids, phenolics, minerals, vitamin C, vitamin E, dietary fibers and other phytochemicals with a proven beneficial effect on human health (Rao and Rao, 2007; Olaniyi *et al.,* 2010, Ramesh *et al.,* 2021a, 2021b). Tomato fruits are also low in fat, calories besides being cholesterol-free with the richness of vitamin A as well, so they are favoured and popular dietary and culinary components across the globe. Versatile health benefits also emphasize the need for tomato fruits in the daily diet of the population especially for poor and developing nations (Burton-Freeman and Reimers, 2011). In this way, nutritional and quality aspects of tomatoes and their consumption as a part of daily diety by the majority of the population make them special and of interest. Although the tomato genome contains the genes that are involved in the production of the pigment anthocyanins, these genes are typically not expressed in most of the commercial tomato varieties. In conventional red colour tomatoes, anthocyanin biosynthesis is switched off and therefore they lack the anthocyanin pigments (Sun *et al.,* 2020). However, the presence of anthocyanins can be seen as limited to the leaves and stems of the tomato plant. During the domestication of the tomato crop and thereafter over some time, the red colour of the fruit along with suitable flavour, texture, and other quality-related aspects was selected based on the consumers' preference (Gonzali *et al.,* 2009). It is, therefore, that despite lots of genetic variability in the colour and for the pigments, conventional and normally cultivated tomatoes do not have anthocyanin pigment in them but they contain lycopene with other carotenoids besides flavonoids and other phenolic compounds.

Anthocyanins: Benefits to plants and human health

Anthocyanins are secondary metabolites produced in different plant parts. They are glycosylated, polyhydroxy, or polymethoxy molecules, formed by two aromatic rings connected by a C3 bridge to a benzene ring. Anthocyanins are a type of flavonoid that are natural plant pigments imparting red, blue and purple colours to flowers, leaves, fruits and some vegetables. They are water-soluble plant pigments that can be synthesized in response to external cues and they are stored in vacuoles and remain stable there due to acidic conditions of vacuoles. Different roles of anthocyanins in plants are very well reviewed in the literature. They are reported for their involvement in attracting pollinators and seed dispersal agents (Koes *et al*., 2005). Their role in plants as antioxidants (being scavengers of reactive oxygen species) is known especially under biotic and abiotic stresses (Naing and Kim, 2021). Additionally, they also exhibit photoprotective effects against UV-B irradiations (Outchkourov *et al*., 2018).

Anthocyanins serve to protect plants against environmental stress whereas they serve as nutraceuticals with multiple he alth benefits for humans. Anthocyanins are gaining a place as a part of the diet and dietary supplements because of the large number of evidence favouring them for their role as antioxidants, free radical scavengers, anti-inflammatory, anti-viral, anti-cancerous, being beneficial in vascular and neuronal disorders and advantageous in conditions like diabetes and obesity (Tsuda *et al.,* 2003; Mauray *et al.,* 2013; Cassidy *et al.,* 2013; Li *et al.,* 2017; Liu *et al.,* 2017; Mattioli *et al.,* 2020).

Purple tomato

Tomato fruit with pigment anthocyanins become purple and therefore they are called purple tomato (Fig 1). In the recent past, purple tomatoes have gained much attention and interest. As stated above that anthocyanin pigments present in purple tomato not only play a protective role for the tomato fruit but also act as a dietary factor with multiple beneficial effects on human health. Researchers, all over the world, are intensely trying to incorporate and improve the content of anthocyanins in tomato fruits. Some other

Source: Butelli *et al.* (2008) and Mes *et al.* (2008).

Fig 1: Purple tomatoes.

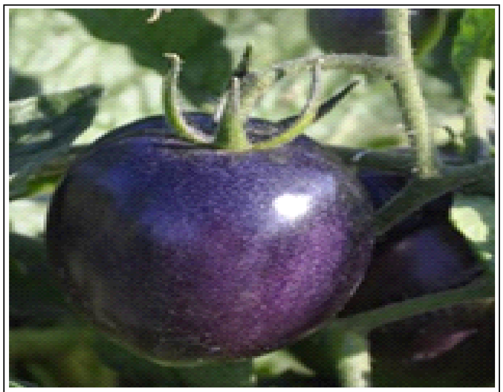
anthocyanin-rich fruits/vegetables of the solanaceous family include eggplant (Todaro *et al.,* 2009), pepper (Tang *et al.,* 2020) and potato (Lal *et al.,* 2021).

Interestingly, wild genotypes of tomato fruits of purple colour with a high level of anthocyanins are known (Daniell 2006). Anthocyanins in tomato fruits are naturally present in wild types of tomato species like *Solanum chilense, Solanum peruvianum* and *Solanum lycopersicoides.* These species produce tomato fruit of green colour but on exposure to suitable light conditions, they accumulate anthocyanins in the peel (Bedinger *et al.,* 2011). In the past, several attempts have been made to biofortify the tomato fruit with anthocyanins but only limited success was achieved. It was then reported that overexpression of flavonoid biosynthesis genes can increase the flavonoids content in tomato fruits (Muir *et al.,* 2001, Schijlen *et al.*, 2006). When this was tried then it increased only the basal level of flavonoids and that too without the initiation of biosynthesis of anthocyanins in tomato fruits. Later on, both traditional, as well as transgenic approaches were put into use for the genesis of purple colour in tomato fruits (Butelli *et al.,* 2008, Mes *et al.,* 2008, Gonzali *et al.,* 2009) as described in subsequent sections.

Approaches to obtain purple tomato fruits

Traditional breeding approach

In the past, different genetic combinations were obtained by crossing *Solanum lycopersicum* with different interfertile wild species. The most stable anthocyanin-rich fruit genotypes were those that were homozygous for both the alleles *i.e.*, Anthocyanin fruit (*Aft*) and Atroviolacea (*atv*) (Georgiev, 1972). Interspecific crosses, involving conventional tomato species with wild-type tomato species, have allowed incorporating anthocyanin pigments in some of the cultivated species (Mes *et al.,* 2008; Gonzali *et al.,* 2009; Myers 2012; Colanero *et al.,* 2020). Tomato accessions namely *Aft, atv,* and *Abg* (Aubergine), with anthocyanin accumulation capacity, have been obtained through breeding programmes. The *Aft* obtained from a cross of *Solanum lycopersicum* and *Solanum chilense* (wild-type) resulted in fruits with anthocyanins present as spots on the peel of the fruit. Similarly, *Abg*as obtained from the cross with wild-type (*Solanum lycopersicoides*) had fruits with the peel of purple colouration. The fruits obtained from the cross with *Solanum cheesemaniae* showed accumulation of anthocyanins in fruit as well as in vegetative tissues. To explore more, breeders have further used the above accessions to enrich the anthocyanin content in tomato fruits. The *Aft* x *atv* and *Abg* x *atv* crosses generated *Aft/Aft atv/atv* and *Abg/- atv/atv* progenies, respectively. Both of these lines accumulated higher anthocyanins in the peel of the fruit (Mes *et al*., 2008, Gonzali *et al*., 2009). The activation of anthocyanin biosynthesis genes in these lines conferred strong purple colouration, especially in the *Aft/ Aft atv/atv* line (Povero *et al.,* 2011). In these fruits, petanin and malvidin-3-(4"-trans-p-coumaroyl)-Rut-5-Glc were the major anthocyanins (> 75%). "Indigo Rose" was the first purple colour tomato variety that was developed through conventional breeding and it was released for cultivation in the year 2012 (Fig 2). Its skin was as dark as an eggplant. The blue colour of this variety was mainly due to the anthocyanin petunidin present on the outer surface of the fruit where the fruit was exposed to direct sunlight.



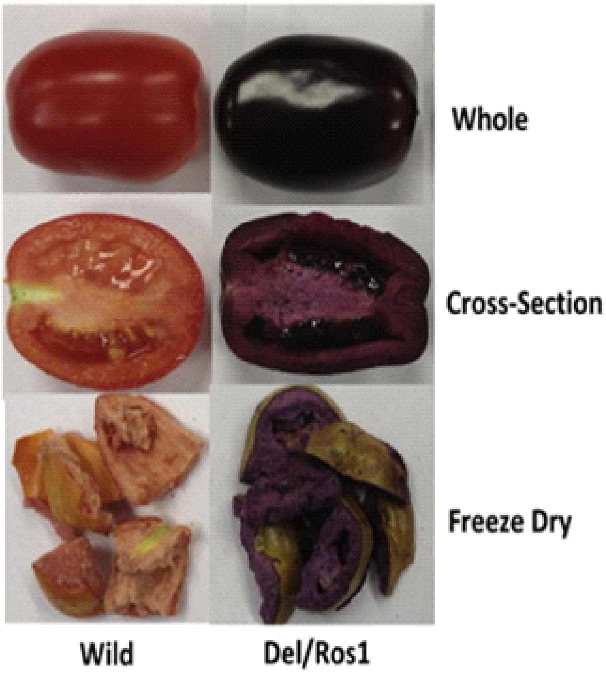
Source: photo by Tiffany Woods, Oregon State University.

Fig 2: A purple tomato fruit of variety "Indigo Rose".

The *Aft/Aft atv/atv* lines have been commercialized as non-genetically modified food with different brand names. 'Sun black' is *Aft/Aft atv/atv* derived line from the cross of *Aft* (accession number LA 1996) and *atv* (LA, 0797) was obtained (Mazzucto *et al.,* 2013) and it was also characterized biochemically (Blando *et al.,* 2019). The comparison of fruits of purple line with wild-type showed the presence of anthocyanins (1 mg g^{-1} dry weight), mainly the petanin (56.6%) and negretein (21.4%), in purple line while there was a complete absence of anthocyanins in wild-type fruits. In addition to this, purple fruits also had higher levels of total phenolics and total flavonoids, especially chlorogenic acid and rutin. The content of total carotenoids was almost similar but the proportions of lutein, α-carotene and β-carotene were higher in purple fruits as compared to wild-type fruits. Another important change was in the content of lycopene pigment as its level was lower in purple tomato fruits. However, the vitamin C (ascorbic acid) content was higher than the fruits of wild-type probably due to better protective action of polyphenols on the oxidation of vitamin C. Overall, the biochemical profiling has depicted better nutritional status of purple tomato fruits.

Transgenic approach

The first genetically engineered tomato was produced in 2008, by overexpressing Delila (*Del*) and Rosea1 (*Ros1*) transcription factors genes from snapdragon (*Antirrhinum majus*) under a fruit specific E8 promoter in MicroTom cultivar, thereby generating a complete *Del/Ros1* purple tomato line (Butelli *et al.,* 2008). These genetically engineered tomato fruits contain significantly higher levels of anthocyanins giving an intense purple colouration to peel as well as to the flesh of fruits (Fig 3). Later, another cross between *Del/Ros1* and a tomato line overexpressing



Source: Butelli *et al*. (2008) and Su *et al*. (2016).

Fig 3: Representative images of the whole, cross-section and freeze-dry of the ripe wild-type (left column) *vs*. the transgenic *Del/Ros1* tomato fruit (right column).

Arabidopsis thalianaMYB12 gene, a transcription factors (to activate the upstream reactions from primary metabolism to flavonoid biosynthesis), generated a new tomato line called 'Indigo' containing almost double the level of anthocyanins (Zhang *et al.,* 2015). This line showed higher expression of phenylpropanoids like chlorogenic acids, flavonols and anthocyanins. Yet another tomato line called 'Bronze tomato' with the expression of stilbene synthase from grapes with higher content of polyphenols like flavonols, anthocyanins, and stilbene was also developed (Scarano *et al.,* 2018). However, so far none of the genetically modified purple tomato lines has been commercialized due to safety issues and concerns.

Overall, both conventionally-bred and the engineered varieties/lines exhibit altered expression of genes that control the anthocyanin biosynthesis. Conventionally bred tomato varieties show anthocyanins in the peel of the fruits whereas the engineered lines produced the pigment in flesh as well as in the peel of the fruits. Both of these approaches have led to the production of new anthocyanin-rich tomato varieties/lines. Some of the famous purple tomato varieties/lines are Black Beauty, Blue Bayou, Blue Chocolate, Blue Gold, Dancing with Smurfs, Dark Galaxy, Fahrenheit Blues, Helsing Junction Blues, Indigo Blue Berries, Indigo Rose, Indigo Ruby, Sun Black and Purple Bumblebee. Anthocyanin content as reported in different fruits and vegetables including the tomatoes (normal and purple) are presented in Table 1.

Table 1: Anthocyanin content in different fruits and vegetables.

Fruit/vegetable	Anthocyanin (mg/100 g fresh weight)
Apple (peel)	10-216
Bilberry	300-690
Blackberry	82-325
Black olives	42-228
Blueberry	25-530
Cabbage (red)	25-322
Cherry	2-450
Cranberry	46-200
Eggplant	8-85
Grape (red)	30-750
Grape (blue)	8-388
Lettuce	2.5-5.2
Onion (red)	23-48
Peach	4.2
Pear	5-10
Plum	2-25
Purple corn	164
Radish (red)	11-154
Raspberry (red)	10-60
Raspberry (black)	76-428
Strawberry	12-55
Tomato (normal)	Nil
Tomato (purple) peel	14-400
Tomato (purple) whole fruit	10-283

Source: Mes *et al.* (2008), Butelli *et al.* (2008), Horbowicz *et al.* (2008), Pascual-Teresa *et al.* (2010), Kayesh *et al.* (2013), Jian *et al.* (2019), Da Silva-Souza *et al.* (2020), Yan *et al.* (2020), Gonzali and Perata (2020).

Purple tomatoes show improved postharvest life

Attempts to improve the shelf-life of tomato fruits during the past few decades have made progress and gains in this direction have been made in terms of not only breeding varieties with more shelf-life but also in terms of management by regulation of storage temperature and atmospheric conditions (Paul and Pandey, 2018). Storage of fruits after their harvest at green mature or breaker stage allowing them to ripe at their own is the most common and conventional approach that is being practiced. At a cellular level, cell wall enzymes (Powell *et al.,* 2003, Paul *et al.,* 2011) and some specific metabolites (Nambeesan *et al.,* 2010, Centeno *et al.,* 2011) have been targeted for improvement of the shelf-life of tomato fruits. Improvement in antioxidant capacity through the enrichment of anthocyanins has also shown promising results in enhancing the shelf-life of tomato fruits. This has been noticed in the case of *Del/Ros1* transgenic tomatoes. This line showed the shelf-life almost double in comparison to wild-type (Zhang *et al.,* 2013, Petric *et al.*, 2018). Further, these tomatoes were also found to be resistant to postharvest pathogens like *Botrytis cinerea*. Studies have shown that the genes involved in the degradation of cell walls like polygalacturonase and galactosidase show reduced expression in purple tomato fruits as compared to usual red tomato fruits. The enhanced antioxidant capacity in purple tomato fruits due to the presence of anthocyanins and other bioactive compounds also contributes effectively in reducing oxidative damage during the period of ripening. All this plays an important role in extending the shelf-life and storability of purple tomato fruits.

A study by Bassolino *et al.* (2013) showed a delay in ripening along with better protection against postharvest pathogens due to the accumulation of anthocyanins in the peel of tomato fruits of *Aft/Aft atv/atv* line. These fruits also showed resistance to *Botrytis cinerea*. In another study by Petric *et al.* (2018), when the fruits of *Aft/Aft atv/atv* line were stored at moderately low temperature (12°C), under appropriate light conditions at the breaker stage, then the fruits showed an enhanced level of anthocyanins and this was without any impairment on any other quality parameters including the carotenoid content, pH, titratable acidity and total soluble solids. Studies on the expression pattern of anthocyanin biosynthesis genes during the postharvest storage showed that the expression of both, structural as well as biosynthetic genes, increased up to three weeks of storage under defined storage conditions. Additionally, alteration in hormonal regulation has also been reported in purple tomato fruits as compared to the red tomato fruits (Petric *et al.,* 2018). A study by Borghesi *et al.* (2016) revealed that in purple tomato fruits climacteric peak of ethylene gets shifted from the usual turning stage to the red stage due to overall delay in the process and progress of ripening.

Conventional red tomatoes are already known for their nutraceutical values and medicinal properties (Rao and Rao, 2007; Li *et al.,* 2017; Przybylska, 2020). Further enrichment of conventional (red colour) tomatoes with a higher level of anthocyanins through traditional or genetic modifications have brought about change not only in colour (purple) but also in texture and other value-added properties such as nutritional value, firmness, flavour, resistance to tensile strength and susceptibility to different diseases. All this has imparted extension in the shelf-life of purple tomato fruits in comparison to conventional red colour tomato fruits (Zhang *et al.,* 2013; Bassolino *et al.,* 2013).

Purple tomatoe in India

Transgenic purple tomato by transfer of two transcription factors *Ros1* and *Del* were developed by taking commercial cultivar Arka Vikas by Maligeppagol *et al.* (2013) at ICAR-Indian Institute of Horticultural Research (IIHR), Bangalore in the Karnataka state of India. The transformed tomato fruits showed a tendency of accumulation of high levels of anthocyanins in flesh and peel of the fruits and thereby phenotypically fruits were dark chocolate to purple in colour but otherwise similar to the wild-type. It was also found

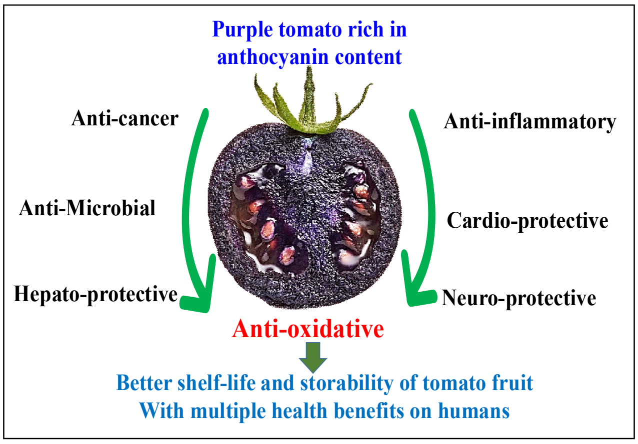


Fig 4: Overall benefits of anthocyanin-rich purple tomato fruits.

that these transgenic fruits showed higher expression of chalcone isomerase(CHI) and flavanoid 3-hydroxylase (F3H) genes in comparison to wild-type fruits resulting in enhanced biosynthesis of anthocyanins. Later, Lonjam (2017) developed nine novel breeding lines of purple tomato by introgressing two specific genes, lycopene enhancing "*dg*" present in chromosome 1 of the genotype BCT-115 and Anthocyanin fruit gene "*Aft*" present in chromosome 10 of the genotype Alisa Craig (*Aft Aft/dg dg*), by following the conventional breeding method at Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal.

Health benefits of purple tomato

Purple tomato fruits provide high nutraceutical value as compared to the classical tomato as it combines the health benefits of the anthocyanins along with other usual and known benefits of phytochemicals, particularly the carotenoids (Su *et al.,* 2016; Scarano *et al.,* 2018; Campestrini *et al.,* 2019). As a result of this, the antioxidant capacity of purple tomato fruits is higher than non-anthocyanin tomato fruits (Gonzali and Perata, 2020). As per Wang *et al.* (2012a, 2012b) and Smeriglio *et al.* (2016), purple tomato fruits provide anti-inflammatory, anti-carcinogenic, antimicrobial and anti-obesity effects in addition to neuroprotective action and ability to reduce the incidences of cardiovascular, metabolic and other degenerative or chronic diseases. The *Del/Ros1* purple tomato line was reported to contain anthocyanins equivalent to blackberries and show a protective role against different types of cancers. Transgenic line 'Bronze tomato' of tomato fruit (with higher content of polyphenols like flavonols, anthocyanins and stilbene) was also reported to exhibit anti-inflammatory properties (Scarano *et al.,* 2018). The strong antioxidant capacity of purple tomato fruits is the basic mechanism behind the above said protective actions (Petric *et al.,* 2018).

FUTURE PERSPECTIVES

In recent years, consciousness towards health and health-related information on food has increased due to advanced social media platforms as well as due to the effect of more and higher literacy. The continuous increase in demand for providing food security and nutritional security particularly in poor and developing nations has made researchers all around the globe think in the direction of providing cost-effective sources of better nutrition and nutrients through the qualitative improvements in fruits and vegetables that are otherwise also consumed on daily basis by the masses (Campestrini *et al.,* 2019). In this context, the purple tomato with higher anti-oxidative properties is gaining interest and popularity.

A better understanding of complex biosynthetic pathways for the synthesis of secondary metabolites including the anthocyanins resulted in the development of purple tomato cultivars/lines around the world. Purple tomato provides extended health benefits in terms of nutrition as it is rich in anthocyanins besides the other flavonoids, carotenoids and other secondary metabolites. Different bioactive compounds as present in purple tomato fruit along with anthocyanins are known to impart anti-cancer, anti-inflammatory, anti-microbial, cardio-protective, hepato-protective, neuroprotective properties, primarily due to enhanced anti-oxidative actions/mechanisms. In addition to this, purple tomato also exhibits extended shelf-life and better storability (Fig 4). Due to all these reasons, the development of purple tomato has been initiated over the globe and its trial on humans is underway. Because of the special place that the tomato fruit enjoys in India, there is a need for timely efforts for the development of purple tomato along with a boost for its integration into the farming practices and utilization in processing sectors.

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Conflict of interest

All authors declare that they have no conflict of interest.

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