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Fresh refrigerated *Tuber melanosporum* truffle: effect of the storage conditions on the antioxidant profile, antioxidant activity and volatile profile

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Abstract

The antioxidant properties of fresh black truffles (*Tuber melanosporum*) (T.) refrigerated at 4 °C under different packaging conditions: air atmosphere (A), reduced pressure (V), mix 1% O₂/99% N₂ (ON) and mix 40% CO₂/60% N₂ (CN) were evaluated during 28 days of storage. The results were compared with the volatile fingerprint determined by SPME-GC/MS and with the phenolic antioxidants characterized by HPLC-MS/MS. The total antioxidant content and the antioxidant activity decreased during the storage, regardless of the packaging method. The principal components analysis (PCA) showed that the total antioxidant content was well correlated with low storage times, high antioxidant activity and three volatile aldehydes. In contrast, 2-propyl-butanoate and 2-nonen-1-ol inversely correlated with the antioxidant activity, as well as gentisic acid, which was the only phenolic antioxidant which increased during the storage. V, CN and ON were always better strategies than A to preserve the freshness of T. However, V is a valid and cheap alternative to normal atmosphere to prolong the shelf life for up to two weeks.

Keywords: black

2 weeks.

Keywords: Black truffle, antioxidants, Antioxidants, volatile Volatile compounds, storage Storage, modified Modified atmosphere packaging

Introduction

During the storage, alteration phenomena of fresh products are mainly due to loss of texture and colour, structure modification, microbial growth and off-flavours formation [1]. Black truffles (*Tuber melanosporum* Vitt.) are hypogeous fungi of great value for their unique and peculiar aroma. After collection, the qualitative and sensory characteristics are preserved unaltered for a very limited period. Truffles are seasonal products. Only by applying a suitable preservation technique the shelf life of fresh truffles can be extended to satisfy the market requests, and many studies have been made in this direction [2].

The oxidation process decreases consumer acceptability of a food product by forming off-flavour, off-flavor, as well as by degrading nutrients, and it produces toxic compounds and dimers or polymers of lipids and proteins. Oxidation in foods can be reduced by removing pro-oxidant compounds such as free fatty acids, metals and oxidized compounds, and by protecting foods from light, air, by applying reduced pressure or by adding antioxidants [3].

Saltarelli et al. [4] investigated refrigeration (4 °C), (4 °C), freezing (-20 °C) (-20 °C) and sterilization as methods of preservation of the more common truffles: *Tuber magnatum*, *Tuber borchii*, *Tuber T. melanosporum* and *Tuber aestivum*. Sugars, proteins, enzymes involved in the metabolism of the fungi and mesophilic bacteria were evaluated and the results showed that the best storage conditions for the preservation of the biochemical and microbiological parameters was the refrigeration at 4 °C. In 2010, Rivera et al. [5] have investigated the possibility to extend the shelf-life shelf life of the truffle (*Tuber T. melanosporum* and *Tuber T. aestivum*) by combining modified atmosphere packaging (MAP) and refrigeration. Later, Amadoro et al. [6] showed that chitosan and ultrasound treatments, used individually or combined with MAP (Modified Atmosphere Packaging), modified atmosphere packaging (MAP), may be an interesting alternative for the storage and postharvest treatment of truffles (*Tuber T. aestivum*).

The antioxidant activity of raw truffles (*Terfezia clavaryi* and *Picoa juniperi*) was reported by Murcia et al. [7]. *Tuber clavaryi* exhibited a more potent activity than *Picoa P. juniperi*. Moreover, freezing affected the radical scavenging activity in a limited way and the canning process caused a significant loss of activity. In the 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS) test, *Tuber clavaryi* showed TEAC (trolox-trolox equivalent antioxidant capacity) capacity (TEAC) values of 4.77, 3.57 and 2.52 for raw, frozen and canned samples, respectively, while TEAC values of 3.91, 2.57 and 0.56 were found for raw, frozen and canned *Picoa P. juniperi* samples, respectively.

The antioxidant activity of the ethanol crude extract of *Tuber indicum* and its sub-fractions (petroleum ether, ethyl acetate, *n*-butyl alcohol and residue) was also investigated [8]. The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical-scavenging radical scavenging activity was found to be in the order *n*-butyl alcohol fraction → residue → ethanol crude extract → ethyl acetate fraction → petroleum fraction → residue → ethanol crude extract → ethyl acetate fraction → petroleum ether fraction, with efficient concentration (EC₅₀) values in the range 1.53–2.87 mg/mL. 1.53–2.87 mg/mL. The ethyl acetate fraction also exhibited the highest ferrous ion chelating activities, with a EC₅₀ value of 0.70 mg/mL. 0.70 mg/mL. More recently, Beara et al. [9] investigated the total phenolic content and antioxidant activity of methanol and water extracts of black summer (*Tuber T. aestivum*) and white (*Tuber T. magnatum*) truffles. The total phenol content varied moderately between the extracts, from 11.7 to 18.7 mg gallic acid equivalents (GAE) per g-gram of dry matter. Differences among the total phenols content and profile in the extracts could be explained by the different extraction conditions applied [10]. The radical scavenging activity of the extracts ranged between inhibition concentration (IC₅₀) values of 149 and 192 µg/mL. 192 µg/mL. In another study, *Tuber T. melanosporum*, *Tuber T. aestivum* and *Tuber T. indicum* were investigated for their total phenols content and inhibition of ABAP-induced lipid peroxidation [11]. Analysed Analyzed truffles contained between 1 and 2 mg-2 mg of phenols per g-gram of dried matter and showed inhibition of lipid oxidation with the following trend: *Tuber T. aestivum* → *Tuber indicum* → *Tuber* > *T. indicum* > *T. melanosporum*.

The aim of this work was to evaluate the effect of different modified-atmosphere packaging (MAP) MAP conditions on the antioxidant properties of fresh samples of *Tuber T. melanosporum* stored at 4 °C 4 °C for 28 days. 28 days. The antioxidant properties (Folin-Ciocalteu, (Folin-Ciocalteu, ABTS, DPPH, FRAP, ferric reducing antioxidant power and Fe-chelating assay), the volatile compounds and the phenolic profile were determined.

Materials and methods

Samples

Intact samples of *Tuber T. melanosporum* Vitt. were harvested in the hilly areas of the Marche Region (Central Italy) with the collaboration of a private company (Acqualagna Tartufi, PU). The fresh samples were manually cleaned and brushed with a wet soft brush and put in polypropylene (PP) vessels (140×175×46

mm) (140 × 175 × 46 mm) containing an absorbent pad. Each vessel contained approximately 100 g of fresh intact truffles. A thermo-sealing machine mod. Rio 39 from Saccardo (Thiene, Italy) was used to pack the vessels with three different atmosphere composition and under reduced pressure. The package was sealed with an antifog film from Nutripack (Milan, Italy), consisting of a polyester film of 12 µm adherent to a polypropylene film weldable on PP homopolymer vessels.

The composition of the different atmospheres was the following: air atmosphere (A) (4) (control); partial vacuum (V); (V); mixture of 1% O₂ / 99% / 99% N₂ (ON), mixture of 40% CO₂ / 60% / 60% N₂ (CN). The sealed vessels were weighed, refrigerated and stored at 4 °C in the dark until analysis. Samples were investigated at time 0 and after 7, 14, 21 and 28 days of storage.

Chemicals and reagents

All reagents used in this study were purchased from Sigma-Aldrich S.p.A. (Milan, Italy) while solvent of analytical grade were obtained from VWR International s.r.l. (Milan, Italy).

Antioxidant activity

Preparation of extracts

An aliquot (5 g) of truffles samples was weighed and blended at slow speed using a laboratory mill (M20 Universal mill, IKA®-Werke IKA®-Werke GmbH & Co. KG, Staufen, Germany). The samples were mixed with 10 mL of ethanol 96% (v/v) and were kept away from the light at room temperature for 24 h. Successively, samples were filtered and ethanol was newly added. The mixture was kept in the dark for other 24 h. After the second filtration, the extracts were gathered into an Erlenmeyer flask and the solvent was removed in a rotary evaporator (BUCHI Italia s.r.l). Finally, the extract was dissolved into 5 mL of ethanol 96% (v/v).

Determination of total antioxidant content

The total antioxidant content was determined by using the Folin-Ciocalteu procedure [12]. Each ethanolic extract was mixed with 0.2 mL Folin-Ciocalteu reagent, 2 mL of Folin-Ciocalteu reagent, 2 mL of water and 1 mL of 15% Na₂CO₃. After incubation for 2 h at 25 °C, the absorbance was measured at 765 nm (UV-Vis 765 nm (UV-Vis Jenway 6300 spectrophotometer, Bibby Scientific Ltd., UK). The total antioxidant content was expressed as mg GAE per g of dry extract.

ABTS^{•+} decolorization assay

The ABTS^{•+} assay was based on the method of Loizzo et al. [12], with slight modifications. The ABTS^{•+} solution, produced from the reaction of ABTS 7 mM and 2.45 mM potassium persulfate, was stored in the dark at room temperature for 12 h before use and diluted with ethanol to reach an absorbance of 0.70 ± 0.05 at 734 nm. An aliquot of 25 µL of extracts at different concentrations were added to 2 mL of diluted ABTS^{•+} solution and the absorbance was measured after 6 min at 734 nm. Ascorbic acid was used as positive control.

DPPH• radical scavenging activity assay

The radical scavenging activity was determined according to the technique reported by Loizzo et al. [12]. Extracts at different concentrations were added to an ethanolic solution of DPPH radical (final concentration was 0.1 mM). The bleaching of DPPH was determined by measuring the absorbance at 517 nm. Ascorbic acid was used as positive control.

Fe²⁺ chelating assay

The chelating activity of the samples was measured following the procedure previously described by Loizzo et al. [13]. Briefly, the extract, FeCl₂ (2 mM) and FerroZine™ (5 mM) were mixed and left at room temperature for 10 min. The absorbance of the Fe²⁺-FerroZine™ complex was measured at 562 nm.

FRAP assay

The FRAP reagent, containing 2.5 mL of 10 mM tripyridyltriazine (TPTZ) solution in 40 mM HCl, 2.5 mL of 20 mM FeCl₃ and 25 mL of 0.3 M acetate buffer (pH 3.6) was freshly prepared [12]. An aliquot (2.5 mg/mL) of samples was dissolved in ethanol and a 0.2 mL of this solution was mixed with 1.8 mL of FRAP reagent. Ethanol solutions of FeSO₄ (50–500 mM) were used to obtain the calibration curve. The absorbance of the reaction mixture was measured at 595 nm and the FRAP value was expressed as mM Fe(II)/g. Butylated hydroxytoluene (BHT) was used as positive control.

Volatile aroma profile

SPME-GC/MS was used to characterize the volatile profile of refrigerated black truffle. The procedure [14–17] was adapted to the conditions of the present experiment. Black truffles (1.5 g) were finely ground using a mill (M20 Universal mill, IKA®-Werke IKA®-Werke GmbH & Co. KG, Staufen, Germany). The powder was introduced in a 10-mL vial and closed with a screw cap equipped with an elastomeric septum. The vial was placed in a heating bath at 40 °C for 10 min. After this time, the SPME fibre (Divinylbenzene/Carboxen/Polydimethylsiloxane, 1 cm, 50/30 µm) from Supelco/Sigma-Aldrich (Milan, Italy) was introduced into the vial and exposed to the headspace of the sample for 15 min. Thermal desorption of the compounds from the fibre took place in the GC injector at 220 °C for 15 min. The injection was performed in the splitless mode (splitless time 0.3 min) at 220 °C. The GC-MS runs were performed with a Varian 3900 gas chromatograph coupled to a Saturn 2100T (Varian, Walnut Creek, CA, USA) ion trap mass spectrometer. The chromatographic separation was performed on a TG-5MS capillary column (Thermo Scientific, 30 m × 0.25 mm I.D., film thickness 0.25 µm). The oven temperature program started at 40 °C during 10 min then was raised to 180 °C at a rate of 3 °C/min and reached 250 °C at a rate of 15 °C/min. The transfer line and trap temperatures were set at 200 °C. The mass spectra were recorded in full scan mode (mass range 31–250 m/z) with a scan rate of 1 scan/sec.

The volatile compounds were analysed with the Varian Workstation software. The identification was confirmed with the chromatographic retention index and the NIST library mass spectra (Version: 2.0; 2002) of pure standard substances.

Phenolic profile by HPLC-HRMS and HPLC-MS/MS

Sample preparation

The ethanol extracts used for the antioxidant assays were stored at -80 °C. For each sample, a 50 mg mL⁻¹ solution was prepared (in triplicate) in the mobile phase A of the HPLC system and vigorously stirred. No further purification was performed.

HPLC-HRMS analysis

The HPLC-HRMS system used consisted of a Thermo Sci. Q-Exactive HRMS instrument coupled to an Agilent 1260 HPLC with a 16 channel DAD detector. The separation was carried out at a flow rate of 1 mL min⁻¹ with a ODS Hypersyl C18 LC column (125 mm × 4.6 mm i.d., 5 µm, Thermo Sci.) protected with a HPLC pre-column filter (Thermo Sci.). A contact closure electronic board allowed to interface the HPLC with the mass spectrometer. The mobile phase consisted of a combination of solvent A (20 mM ammonium formate, 0.1% formic acid in water, v/v) and B (sat. ammonium formate, 0.1% formic acid in acetonitrile, v/v). The gradient was as follows: from 5% B at 0 min to 25% B (v/v) at 21 min, then to 95% B at 22 min until 27 min, to 5% at 28 min, followed by a re-equilibration step (5% B) at 32–35 min. The DAD recorded spectra from 210 to 600 nm and provided real-time monitoring at 280 nm (±2 nm). A post-column flow splitter was used to feed both analyzers in parallel (DAD and HRMS) at a fixed ratio. For Full-MS analysis, the mass spectrometer was operated in negative ionization mode using the following conditions: sheath gas at 20 (arbitrary units), aux gas at 5 (arbitrary units), aux temperature 250

°C, 250 °C, spray voltage at -3.5 kV, -3.5 kV, capillary temperature at 320 °C 320 °C and RF S-lens at 65. The mass range selected was from 100 to 1000-1000 m/z with a Full-MS-full MS set resolution of 70000 (@200 m/z), 70,000 (@200 m/z), AGC target at 1e6, max. injection time of 200 ms-200 ms. Eighteen substituted phenolic acids, cinnamic acids and flavan-3-ol standards were, singularly and in their mix, analyzed prior to the samples analysis.

HPLC-FullMS-dd-MS/MS analysis

Data dependent HPLC-MS/MS-HPLC-MS/MS experiments were run in negative ionization mode: FullMS-full MS parameters were kept as shown, MS/MS AGC target 3e5, max. injection time 200, FTMS set resolution 17500, 17,500, loop count 5, isolation window 3 m/z , 3 m/z , isolation offset 1 m/z , 1 m/z , and normalized collision energy 45 eV-45 eV. For data dependent settings: minimum AGC target 3e3, apex trigger 2 to 8 sec, 2-8 s, charge exclusion 3-8-3-8 and higher, dynamic exclusion 10 sec, 10 s, "if idle" setting set to "pick others". Lock masses were included in the instrument method in both positive and negative mode. 18 substituted phenolic acid, cinnamic acids and flavan-3-ol standards were singularly analyzed prior to the samples analysis.

Data acquisition and processing

The HPLC-DAD-HPLC-DAD data were collected and analyzed by OpenLab software while the MS data and results were collected and analyzed by Xcalibur 3.1 software and Compound Discoverer (Thermo Sci.). MzCloud on-line-online database and fragmentation list prepared by us by standard injection were also employed for the compounds' identification and confirmation.

Statistical analysis

All samples were analysed-analyzed in triplicate. Data were expressed as mean \pm standard mean \pm standard deviation and were analysed-analyzed using one-way analyses of variance (ANOVA). Significant differences between groups were determined with ANOVA with Bonferroni correction. A P value < 0.05 < 0.05 was considered significant. Correlation of phenolic antioxidants relative abundances (HPLC-MS (HPLC-MS EIC integrations) with the antioxidant activity assays and volatiles was done by multivariate analysis (PCA) [principal components analysis (PCA)] using Unscrambler 10.4 software (Camo Software, 2016 ed., Oslo, Norway). All the variables were normalized before elaboration.

Results and discussion

Antioxidant activity

Several in vitro methods were developed for measuring the antioxidant status of food products. These tests differ in the generation of radicals and/or or target molecules, and in the way end points are measured. Due to the in vivo oxidative process complexity, the application of a single method for the assessment of the oxidation state is not enough, since the level of a single antioxidant in food does not necessarily reflect the antioxidant activity. For this reason, choosing an adequate assay is critical [18]. The antioxidant activity of truffle samples under different package condition and storage time was assessed by using several in vitro methods, such as ABTS, DPPH, Fe-chelating and FRAP assay. A concentration-response relationship was observed for all tested samples (Tables 1-3 (Tables 1, 2, 3).

The total antioxidant content was evaluated by the Folin-Ciocalteu-Folin-Ciocalteu method. The experimental data (Table 1 (Table 1) revealed that the total antioxidant content decreased during the storage regardless of the packaging adopted. The ON samples exhibited the significantly highest total antioxidant content with values ranging 48.6-33.3-48.6-33.3 GAE per g-gram of dry extract from 7 to 28 d-days of storage, respectively. The correlation analysis revealed a Pearson's correlation coefficient of 0.96 for ON samples.

The total antioxidant content on day 7 and day 14 was significantly lower in the A, A, V and CN samples than ON. Afterwards, on day 21, the antioxidant content was higher in the ON sample than in A, A, V and CN. On day 28, the ON samples showed the highest total antioxidant content with respect to the others.

There is a limited number of investigations regarding the antioxidant content of truffles. The species studied were *Terfezia boudieri* [19, 20], *Tuber-T. aestivum* [9, 11, 21], *Tuber-T. magnatum* [9], *Tuber-T. melanosporum* and *Tuber-T. indicum* [11]. Literature data were barely comparable because of different

extraction methods and unit of measurement. At our knowledge, only the paper of Villares et al. [11] reported data about the phenolic content of truffles. Values of 1.88, 1.52, and 1.20 mg GAE per g of dried matter were found for *Tuber T. aestivum*, *Tuber T. indicum* and *Tuber T. melanosporum*, respectively.

The radical scavenging ability was evaluated with the DPPH and ABTS tests (Table 2). Generally, a reduction in bioactivity was found during the storage period (from 7 to 28 days of storage). The significantly highest ABTS radical scavenging ability was observed in the V sample after 7 and 14 days of storage (with IC₅₀ values of 1.8 and 3.4 µg/mL, respectively). On day 21, the CN samples showed the significantly highest ABTS radical scavenging ability. Afterwards, on day 28, the V samples showed the significantly highest ABTS activity.

Tuber melanosporum packed with CN maintained the radical scavenging activity significantly higher than truffle packed with ON from 7 to 28 days of storage.

The same trend was registered also in the DPPH assay. The sample V on day 7 and 14 showed the highest DPPH radical scavenging activity with IC₅₀ value of 55.7 µg/mL and 63.1 µg/mL, respectively.

The samples in A atmosphere showed the significantly lowest ABTS radical scavenging ability and lowest DPPH radical scavenging activity from 7 to 28 days. Among the investigated methods of packaging, the CN samples preserved the antioxidant compounds better than A and ON samples.

Truffles packaged in different way were also subjected to Fe-chelating activity assays (Table 3). During the Fenton reaction, iron is involved into redox processes that generates oxygen free radical [22]. One of the possible approaches to limit ROS is to reduce iron. Generally, the ability of extracts to chelate iron decreased during the storage. The Fe-chelating activity was determined by measuring the formation of the Fe-FerroZine™ complex, and these activities were compared with the chelating activity of EDTA (IC₅₀ value of 1.3 µg/mL). The fresh truffle extract exhibited the highest activity with IC₅₀ value of 21.7 µg/mL followed by ON after 7 and 14 days of storage (IC₅₀ value of 29.5 µg/mL and 38.9 µg/mL, respectively). On days 21 and 28, CN samples showed the significantly highest Fe-chelating activity, whereas the A samples showed the significantly lowest activity from 7 to 28 days of storage.

The redox potential of phytochemicals plays a crucial role in determining the antioxidant properties of the extract. For this reason, the FRAP assay was performed. The fresh truffle extract showed a FRAP antioxidant power 1.4-time higher than those reported for the positive control, BHT. Noteworthy, the ON sample at 7 days of storage exhibited a FRAP value quite similar to the positive control.

On 14 and 21 days of storage, A, V and ON samples showed significantly higher FRAP antioxidant power than CN samples. On 28 days of storage, ON samples showed a significantly higher FRAP antioxidant power than the V and CN samples (Table 3).

PCA

The main identified volatile compounds found in the samples were alcohols (1-octen-3-ol, 2-nonen-1-ol), aldehydes (2,2-dimethyl-4-octenal, heptanal, octanal, 2-methyl-3-methylidenecyclopentane-1-carbaldehyde, octenal), a ketone (3-(5-methyl)-heptanone), one ester (2-propyl-butanoate) and benzene derivatives (methoxybenzene, 3-methyl-methoxybenzene, 1,2-dimethoxybenzene) (Table 4).

Besides, five phenolic acids were identified by HPLC-HRMS analysis and are shown in Table 5.

The results of the PCA are displayed in Fig. 1. The biplot of Fig. 1 is built on a model accounting for 52% of the total variance (PC1 and PC2). It shows the clustering of the samples and the loading of variables related to the antioxidant activity tests, the phenolic acids and the volatile compounds. The Folin-Ciocalteu index correlated with low storage times, with four of the phenolic acids (gallic, *p*-hydroxybenzoic, *p*-hydroxybenzoic, *o*-hydroxybenzoic and a dihydroxybenzoic acid isomer) and with three aldehydes (2,2-dimethyl-4-octenal, 2-methyl-3-methylidenecyclopentane-1-carbaldehyde and octenal). The samples were gradually shifted towards negative values of PC1 according to increasing storage

time. Until the first week, all the samples (but A1) were positioned on the positive side of PC1, which can be associated with freshness. The volatile compounds that inversely correlated with the antioxidant activity of the samples were heptanal, 2-propyl-butanoate and 2-nonen-1-ol. These compounds positively correlated with the normal atmosphere treatment, confirming that this was not the best procedure to store the black truffle; in fact, A1 was the worst sample among those of the first week, as freshness is concerned.

Unexpectedly, gentisic acid (but not its isomer) was the only phenolic acid increasing at week four; thus, its overall trend inversely correlated with the antioxidant activity.

Conclusion

The model built up on the multivariate statistical analysis of volatile compounds, phenolics and antioxidant performance allowed to investigate successfully the effects of the storage conditions on quality of *Tuber T. melanosporum*, one of the most expensive fresh food products.

The evaluation of the antioxidant activity of food products is context-dependent since the oxidative stress is a complex process. The capacity and potency of antioxidants, as obtained by various methods, do not necessarily correlate among them [23].

Three volatile compounds can be associated with the high antioxidant properties of freshly packaged truffles. They are all aldehydes: 2,2-dimethyl-4-octenal, 2-methyl-3-methylidenecyclopentane-1-carbaldehyde and octenal. Thus, they can be considered as natural chemical quality markers for the fresh black truffle.

Two volatile compounds can be considered as markers of the decay of the raw black truffles subjected to the storage at refrigerated temperature: 2-propyl-butanoate is an ester produced upon fermentation of food from animal [24] and plant [25] origin; 2-nonen-1-ol is a monounsaturated alcohol commonly present in mushrooms [26] increasing after fermentation [27] or fermented food processing [28]. Both are positively related to the decrease of the antioxidant properties and total antioxidant content of the samples. Gentisic acid (2,5-dihydroxybenzoic acid) along with one of its isomers and *o*- and *p*-hydroxybenzoic acid have been previously found in edible mushroom varieties [29] and in medicinal ones [30]. Moreover, *o*- [31] and *p*-hydroxybenzoic [32] acid derivatives have been also associated to many metabolic inhibition pathways and specifically as inhibitors of tyrosinase enzymatic hydroxylation of phenols into *o*-diphenols *o*-diphenols and the oxidation of 3,4-catechol derivatives to benzoquinones. Gentisic acid also showed inhibition effects on polyphenol oxidases [33]. The increasing trend of gentisic acid during the storage is however is, however, hard to explain. Tentatively, its oxidation during the storage may be counterbalanced by the degradation of higher molecular weight analogues analogs or by enzymatic hydroxylation of hydroxybenzoic acid derivatives [34].

Compared to the storage of black truffle in a headspace consisting of normal atmosphere, more valid alternatives can be proposed. Reduced pressure seems to be a valid and cheap alternative to the modified atmosphere used in this experiment to prolong the shelf life of raw *Tuber T. melanosporum*. This consideration is based on the results related to the extension of the antioxidant properties and native volatile profile of the samples for up to two weeks 2 weeks compared to normal atmosphere. Moreover, the vacuum technology is cheaper than MAP, however however, showing a similar performance.

The extension of the shelf life of raw black truffles from a few days up to two weeks 2 weeks is very important to small and medium enterprises exporting the fresh product to international and overseas markets because it implies lower delivery costs.

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Compliance with ethical standards

Conflict of

interest:

interest

The Authors authors declare that they have no conflict of interest.

Compliance with ethics

requirements:

requirements

All authors declare that this article does not contain any studies with human or animal subjects.

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Fig. 1 PCA of the antioxidant activity (ABTS, DPPH, FRAP, Fe-chelating and FC), identified antioxidants and volatile compounds (circled variables) in relation to different storage conditions. A, A air atmosphere; V, V reduced pressure; ON, ON mix of 1% O₂/99% N₂; CN, CN mix of 40% CO₂/60% N₂. The days of storage (d) are reported as follows: 0; time 0; 1, 7 d; 2, 14 d; 3, 21 d; 4, 28 d. Abbreviations used for the identified antioxidants: pOH-BA = pOH-BA p-hydroxybenzoic acid, OH-BA = o-hydroxybenzoic acid, GeA = gentisic acid, GaA = gallic acid, diOH-BA = other dihydroxybenzoic acid

Table 1 Total antioxidant content (mg GAE per g gram dry extract) of *Tuber melanosporum* at different storage conditions

Period of storage (days)	Period of storage (days)	F	Total antioxidant content (mg/g extract)				
			F	A	V	CN	ON
0	0	54.7 ± 0.8					
7	7	36.7 ± 0.336 .7 ± 0.3 ^{b,d}	34.0 ± 0.234 .0 ± 0.2 ^d	34.2 ± 0.334.2 ± 0.3 ^d	48.6 ± 0.348.6 ± 0.3 ^{a,b,c}		
14	14	36.0 ± 0.53 .0 ± 0.5 ^b	29.3 ± 0.229 .3 ± 0.2 ^{a,d}	32.0 ± 0.132 .0 ± 0.1 ^{b,d}	48.0 ± 0.648 .0 ± 0.6 ^{a,b,c}		
21	21	35.3 ± 0.535 .3 ± 0.5 ^{b,c}	29.2 ± 0.329 .2 ± 0.3 ^{c,d}	24.0 ± 0.124.0 ± 0.1 ^{c,d}	38.1 ± 0.338 .1 ± 0.3 ^{b,c}		
28	28	23.3 ± 0.323 .3 ± 0.3 ^{b,d}	29.2 ± 0.329 .3 ± 0.3 ^{c,d}	21.3 ± 0.321.3 ± 0.3 ^d	23.3 ± 0.233 .3 ± 0.2 ^{a,b,c}		

Data are expressed as means ± standard deviation (n = 3). Values within columns followed by different superscript letters (a, b, c, d) differ significantly from each other at $P < 0.05$.

F fresh truffle, A truffles packed in ambient atmosphere, V truffles packed under partial vacuum, CN truffle packed with 60% N₂ and 40% CO₂, ON truffle packaged with the 1% O₂ and 99% N₂

Table 2 Radical scavenging ability of *Tuber melanosporum* (IC₅₀ µg/mL)

Period of storage (days)	Period of storage (days)	ABTS (µg/mL)				DPPH (µg/mL)			
		A	V	CN	ON	A	V	CN	ON
0	0	38.5 ± 2.4				42.4 ± 2.2			
7	7	138.9 ± 2.7138.9 ± 2.7 ^{b,c,d}	1.8 ± 0.31.8 ± 0.3 ^{a,c,d}	41.9 ± 1.141.9 ± 1.1 ^{a,b,d}	84.3 ± 1.684.3 ± 1.6 ^{a,b,c}	>400	55.7 ± 1.255.7 ± 1.2 ^{c,d}	55.7 ± 1.255.7 ± 1.2 ^{c,d}	71.1 ± 1.671.1 ± 1.6 ^{b,d}
14	14	350.3 ± 4.8350.3 ± 4.8 ^{b,c,d}	3.4 ± 0.83.4 ± 0.8 ^{a,c,d}	57.1 ± 1.857.1 ± 1.8 ^{a,b,d}	93.1 ± 1.393.1 ± 1.3 ^{a,b,c}	>400	63.1 ± 1.663.1 ± 1.6 ^{c,d}	63.1 ± 1.663.1 ± 1.6 ^{c,d}	89.2 ± 1.889.2 ± 1.8 ^{b,d}
21	21	574.0 ± 4.9574.0 ± 4.9 ^{b,c}	85.8 ± 1.585.8 ± 1.5 ^{a,c}	60.0 ± 1.660.0 ± 1.6 ^{a,b}	>400	>400	84.5 ± 1.984.5 ± 1.9 ^{c,d}	84.5 ± 1.984.5 ± 1.9 ^{c,d}	107.2 ± 1.8107.2 ± 1.8 ^{b,d}
28	28	603.3 ± 4.3603.3 ± 4.3 ^{b,c}	98.3 ± 2.398.3 ± 2.3 ^{a,c}	305.3 ± 2.9305.3 ± 2.9 ^{a,b}	>400	>400	151.0 ± 2.2151.0 ± 2.2 ^{c,d}	151.0 ± 2.2151.0 ± 2.2 ^{c,d}	108.1 ± 2.1108.1 ± 2.1 ^{b,d}

Data are expressed as means \pm standard deviation ($n = 3$). mean \pm standard deviation ($n = 3$). Values within columns followed by different superscript letters (^{a,b,c,d}) (a, b, c, d) differ significantly from each other at $P < 0.05$ < 0.05

Ascorbic acid in ABTS test IC₅₀ 1.7 $\mu\text{g/mL}$, 1.7 $\mu\text{g/mL}$, in DPPH test IC₅₀ 2.0 $\mu\text{g/mL}$ 2.0 $\mu\text{g/mL}$

F fresh truffle, A truffles packed in ambient atmosphere, V truffles packed under partial vacuum, CN truffle packed with 60% N₂ and 40% CO₂, ON truffle packaged with the 1% O₂ and 99% N₂

Table 3 Ferrous ions and reducing power of *Tuber melanosporum* extract ($\mu\text{g/mL}$) (μM 2.5 mg/mL)

		Period of storage (days)	Fe-chelating activity	($\mu\text{g/mL}$)		FRAP	(μM Fe(II)/g at truffle extract concentration of	Period of Storage (days)	2.5 mg/mL)	
F	A		V	CN	ON	F	A	V	CN	ON
02	± 2.42				4.66 ± 6.66					
7	± 2.4				6.66 ± 2.2					
14										
21										

		.6 ± 4. 0 ^b ,c, d	.1 ± 2. 3 ^a ,c, d	± 1. g ^a ,b, d	.4 ± 1. 5 ^a ,b, c	± 1. g ^c 8 ⁹ -5	2 ^c	.2 ± 1. 8 ^a ,b, d	± 2. 0 ^c
28		62 0. 5. ± 4. 06 20 .5 ± 4. 0 ^b ,c, d	19 8. 6. ± 2. 91 98 .6 ± 2. 9 ^a ,c, d	13 4. 5. ± 2. 01 34 .5 ± 2. 0 ^a ,b, d	13 6. 7. ± 2. 61 36 .7 ± 2. 6 ^a ,b, c	11 3. 4. ± 1. 81 13 .4 ± 1. 8 ^c	12 1. 7. ± 2. 01 21 .7 ± 2. 0 ^d	12 8. 4. ± 2. 21 28 .4 ± 2. 2 ^a ,d	10 4. 4. ± 2. 11 04 .4 ± 2. 1 ^b ,c

Data are expressed as means ± standard deviation (n = 3). mean ± standard deviation (n = 3). Values within columns followed by different superscript letters (a,b,c,d) (a, b, c, d) differ significantly from each other at $P < 0.05$

BHT in Fe-chelating assay IC₅₀ 1.3 µg/mL, 1.3 µg/mL, in FRAP assay 63.2 µM Fe (II)/g 63.2 µM Fe(II)/g

F fresh truffle, A truffles packed in ambient atmosphere, V truffles packed under partial vacuum, CN truffle packed with 60% N₂ and 40% CO₂, ON truffle packaged with the 1% O₂ and 99% N₂

Table 4 Main volatile compounds identified in fresh samples of *Tuber melanosporum* stored at 4 °C 4 °C 2- propyl-butanoate heptanal methoxybenzene 1-octen-3-ol octanal 3-methyl-methoxybenzene 2-methyl-3-methylidenecyclopentane-1-carbaldehyde octenal 2-nonen-1-ol 1,2-dimethoxybenzene

Number	Volatile compounds
1	4-(2,2-dimethyl)-octenal
2	2-Propyl-butanoate
3	Heptanal
4	Methoxybenzene
5	1-Octen-3-ol
6	3-(5-methyl)-heptanone
7	Octanal
8	3-Methyl-methoxybenzene
9	2-Methyl-3-methylidenecyclopentane-1-carbaldehyde
10	Octenal
11	2-Nonen-1-ol
12	1,2-Dimethoxybenzene

Table 5 Phenolic compounds identified in crude ethanolic extracts of *Tuber melanosporum*

Name	LC-MS LC-MS r.t. (min)	av. [M-H] ⁻ (m/z) (m/z)	Prevalent MS/MS fragments (m/z) (ESI (-), NCE = 15 eV) (m/z) (ESI (-), NCE = 15 eV)**
p-Hydroxybenzoic acid	6.7	137.0244	137.024 (<1), (<1), 93.035 (100)
o-Hydroxybenzoic acid (salicylic acid) (salicylic acid)	8.5	137.0244	137.024 (69), 93.035 (34)
2,5-Dihydroxybenzoic acid (gentisic acid) (gentisic acid)	3.3	153.0193	153.019 (18.2), 109.030 (100)
Gallic acid	2.6	169.0142	169.014 (6.5), 125.024 (100)
Other dihydroxybenzoic acid (*) acid*	6.8	153.0193	153.019 (100), 109.030 (51.3)

(*) ~~protocatechuic~~ * Protocatechuic acid (3,4 -) r.t. is 4.8 min, 4.8 min, so this can only be assigned to 3,5- or 2,3-dihydroxy benzoic acid. (**) ~~Intensity~~ acid

** Intensity expressed in % over the most intense ion. (***) ~~confirmed ion~~

*** Confirmed only by standard injection (retention time and HRMS matching)