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Carvone Containing Essential Oils as Sprout Suppressants in Potato (*Solanum tuberosum* L.) Tubers at Different Storage Temperatures

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Abstract

Sprout suppressant capacities of caraway (*Carum carvi* L.), dill (*Anethum graveolens* L.), and spearmint (*Mentha spicata* L.) essential oils containing high levels of carvone were studied at different storage temperatures (5, 10, and 15 °C) and compared to two chemical sprout inhibitors chlorpropham (CIPC) and S-(+)-carvone. Amongst the essential oils tested, caraway oil was the most effective sprout inhibitor and prevented sprouting up to 180 days at all storage temperatures. CIPC treatment in preventing sprouting was very effective only at low-temperature conditions, while its effect diminished at 15 °C and sprouting began after 120 days of storage. Dill oil prevented sprouting effectively at 15 °C for more than 135 days, and less than 20% of tubers exhibited sprouting. Sprout inhibitory effects of peppermint oil and S-(+)-carvone decreased with increasing storage temperature. All treatments significantly decreased weight loss as compared to the control. The weight loss of caraway oil treated tubers was 36.1%, 46.2%, and 49.6% at 5, 10, and 15 °C, respectively, being lower than that of the control. The peelings of tubers treated with essential oils showed lower carvone residue levels than those of S-(+)-carvone applied tubers. The CIPC residue levels of tubers stored at 5 °C were 16 ppm, being greater than the allowed threshold levels in European countries. It was concluded that using caraway and dill oils decreased weight losses substantially and prevented sprouting for long-term storage at up to 15 °C.

Keywords Carvone · Essential oil · Tuber-sprouting · Tuber weight loss

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Introduction

Potato is a major food crop throughout the world, and with nearly 388 million tonnes of production in 2017, it ranks fourth in the world production after rice, wheat and maize (Anonymous 2017). It is estimated that less than 50% of potatoes grown worldwide are consumed fresh. The rest are processed to obtain food ingredients, starch, alcohol and animal feed or re-used as seed tubers (Anonymous 2016). Thus, tubers need to be stored for a long time to ensure sufficient supplies until the next harvest. Respiration of tubers and breakdown of dormancy during storage result in sprouting (Suhag et al. 2006). Weight loss, tuber quality, the percentage of marketable tubers and their nutritional quality are affected by sprouting and consequently determine economic value of potatoes during storage (Friedman and McDonald 1997). Excessive sprouting can lead to a physiological aging of tubers resulting in yield losses if such tubers are to be used as seed tubers for planting (Katundu et al. 2007). Effective sprout control is a major factor in managing stored potato quality. Cold temperature storage (2 to 4 °C) not only delays sprouting but also results in unacceptable tissue sweetening (Coffin et al. 1987). Successful long-term storage of potatoes necessitates the use of sprout inhibitors in combination with proper storage management. Chlorpropham (CIPC, isopropyl 3-chlorocarbanilate) is the most effective chemical sprout inhibitor registered for use in potato storage (Kerstholt et al. 1997). However, there are growing concerns with regard to the levels of CIPC residues on potato tubers and its potential negative impacts on human health and the environment. The maximum residue limit (MRL) for fresh potatoes in the USA was reduced from 50 to 30 ppm, and in Europe, an MRL of 10 ppm has been established (Kleinkopf et al. 2003; EPA 2012). Moreover, potato seed tubers cannot be treated or stored in CIPC storage rooms because of the chemical's long-term negative effect on field sprouting of tubers (Conte et al. 1995). Due to the increasing concern for consumer health and safety, there is an increasing interest in identifying environmentally friendly methods to inhibit potato sprouting. Treatment with gamma-irradiation and low energy electrons (Todoriki and Hayashi 2004; Teper-Bamnolker et al. 2010), ethylene (Prange et al. 1998), ozone (Daniels-Lake et al. 1996) and H_2O_2 (Afek et al. 2000) are recommended to inhibit sprouting, but each has certain disadvantages.

Essential oils (EOs) in herbs and spice crops or monoterpenes have been investigated for sprout suppression capacity (Coleman et al. 2001; Fraizer et al. 2004; Song et al. 2004; Silva et al. 2007; Gomez et al. 2010; Şanlı et al. 2010; Song et al. 2008; Gomez-Castillo et al. 2013). Studies indicate that carvone is an effective inhibitor of sprouting in potatoes (Oosterhaven 1995; Sorce et al. 1997; Song et al. 2008). Carvone contains two enantiomers: S-(+)-carvone and R-(−)-carvone. S-(+)-carvone is the major compound in caraway and dill seed oil (Hartmans et al. 1995). R-(-)-carvone is present in spearmint oil (Leitereg et al. 1971). To date, only the monoterpene (S)-(+)-carvone, a chemical produced from caraway seeds and described as a volatile sprout suppressant (Beveridge et al. 1981), has been commercially marketed (Talent™) in some European countries (Gomez-Castillo et al. 2013). The treatment of potato tubers with S-(+)-carvone led to the growth inhibition of the potato sprouts through the key enzyme in the mevalonate pathway, 3-hydroxy-3-methylglutaryl coenzyme A reductase (HMGR) (Oosterhaven et al. 1993). However, the high cost of its production and its application, compared with traditional sprout suppressants such as CIPC, have limited its use.

On the other hand, EOs evaporate rapidly in the presence of air, moisture and high temperatures, and thus some of their active components are degraded (Pillmoor et al. 1993). A more frequent wick application (using air wick freshener apparatus for evaporation of liquid material) of EOs at low concentration may provide greater efficacy. The sprout suppression effects of many EOs and their major compounds have been studied, but only a few investigations have been conducted on the application methods for increasing the effectiveness of EOs. Therefore, the current study was conducted to investigate the potential of caraway, dill and spearmint EOs in preventing sprouting using an air wick freshener apparatus in a storage system that mimicked actual storage conditions in terms of storage temperature, relative humidity (RH) and ventilation.

Materials and Methods

Plant Materials

Potato (*Solanum tuberosum* L.) cultivar "Agria" which is commonly grown in Turkey was used as plant material in the study. Potato tubers were produced in Suleyman Demirel University, Isparta, Turkey, under standard cultural conditions in 2008. Freshly harvested healthy potato tubers weighting from 80 to 120 g/tuber were cured in dark conditions for 2 weeks, during which the temperature was gradually reduced from 20 to 8 °C. All EOs, caraway, dill and spearmint, used in this study, were extracted from corresponding plant materials at Agriculture Faculty of Suleyman Demirel University. S-(+)-Carvone (2-methyl-5-ısopropenyl-2-cyclohexen-1-one) was purchased from Sigma-Aldrich, Canada, and a liquid formulation (Gro-Stop SC 300 (B.V. Luxan)), of 240 g/l CIPC and 40 g/l IPC, was purchased from Poland.

Isolations of the Essential Oils

Air-dried materials of spearmint and seeds of caraway and dill were extracted in water for 3 h, using a clevenger-type apparatus in accordance with the description of the British Pharmacopoeia (1980). The EO constituents of the water extract were determined by gas chromatography/mass spectrophotometry (GC/MS) analyses. The main components of the EOs were carvone and limonene for caraway (carvone 55.1% and limonene 29.9%), dill (carvone 73.0% and limonene 26.5%) and spearmint (carvone 76.9% and limonene 6.7%).

CIPC, S-(+)-Carvone and Essential Oil Preparation and Wick Applications

S-(+)-Carvone and CIPC were applied at recommended doses of 600 ml (Hartmans et al. 1995) and 20 g (Anonymous 1993) per 1000 kg potato tubers, respectively. Application doses of caraway, dill and spearmint EOs were calculated according to their EO and carvone contents. The application doses of compounds used in the study were calculated for 20 kg tubers for a period of 6-month storage (see Table 1). All compounds used in the study were applied in aerosol form using an air wick freshener apparatus (time regulated) for homogenous distribution of the compounds in storage

Table 1 The application time and doses of CIPC, S-(+)-carvone and essential oils

Applications	Carvone content (%)	Number of Appl./ Appl. times	Dosage per application (ml/20 kg)	Total amount per 20 kg	Wick apparatus working time (min/number)	Application time (h/day)
CIPC	–	3×/2 months	0.4	1.2[a]	30 min/1	7.5
S-(+)-carvone	95	24×/week	0.5	12.0[b]	30 min/1	6.25
Caraway EO	55.1	24×/week	0.96	21.8	7.5 min/1	10
Dill EO	73.0	24×/week	0.69	16.6	7.5 min/1	10
Spearmint EO	79.6	24×/week	0.63	15.1	7.5 min/1	10

[a] CIPC dosage, 60 ml/1000 kg tuber (Anonymous 1993)

[b] S-(+)-carvone dosage, 600 ml/1000 kg tuber (Hartmans et al. 1995)

atmosphere. EOs (caraway 21.8 ml, dill 16.6 ml and spearmint 15.1 ml) were filled into the wick tubes (250 ml) with pressure gases after being dissolved with ethanol, while CIPC and S-(+)-carvone were filled in their pure forms. Wick machine working times were calculated separately for each application and spraying amount (32 ml/per spray) and are given in Table 1. To determine the effects of pressure gases and alcohol, two control groups with three replications were also tested at 15 °C storage temperature.

Storage Conditions

The experiment was carried out in different storage rooms set at 5, 10 and 15 °C with 85% relative humidity for 6 months. Plastic containers (100 L) were used for the storage of potato tubers, and 200 tubers (20 kg) were placed in each plastic container. The lids of containers were tightly closed using silicon. A total of 18 containers (6 treatments × 3 replications) were put in each storage room. Ventilation of containers with a 12-V fan was performed through a vertically placed PVC pipe attached to the ceiling of the storage room. All covers were drilled (1 cm diameter) and connected to the fan through a hose. The airflow of the containers in the ventilation system was consistent with a commercial storage rate (2.5–5.0 L/min/kg of potatoes). All the containers were ventilated for 2 h every day, and the fans were turned off for 38 h after treatments. During storage, CO_2 and O_2 levels were controlled so that they did not exceed certain limits, which were not higher than 0.3% for CO_2 and not lower than 18.4% for O_2. All the treatments including the untreated control were held under the same conditions for 180 days.

The sprouting and weight losses of tubers were determined at 15-day intervals. When the longest sprout was greater than 2 mm in length, the tuber was considered to be sprouted (Salimi et al. 2010). Sprout suppression was measured at the end of storage. The mean sprout suppression effect was determined and expressed on a sliding scale identified as follows: (1) bad, (2) insufficient, (3) almost sufficient, (4) sufficient, (5) amply sufficient, (6) good and (7) excellent (Hartmans et al. 1995). CIPC and carvone residues were analysed in composite samples of ten tubers. Unwashed potato peelings and peeled tubers were analysed separately at the end of the storage using the HPLC method, described earlier (Ezekiel and Singh 2007).

Data were analysed according to General Linear Model (SAS 1998), and the means were separated using Duncan's Multiple Range Test at a 5% level of significance.

Results

Inhibition of Sprouting

Effects of pressure gases and alcohol on sprouting did not differ significantly from the control (Table 2). For all storage temperatures, caraway EO had the most efficient sprout inhibitory effect and sprouting was inhibited until the end of the storage period. CIPC, dill EO, spearmint EO and S-(+)-carvone-treated tubers stored at 5 °C inhibited sprouting very efficiently (until 5 months), while non-treated potato tubers began to sprout after approximately 3 months of storage (Fig. 1). While the control tubers had nearly 100% sprouting, the tubers treated with CIPC, dill EO, spearmint EO and S-(+)-carvone exhibited low sprouting levels (4.0, 6.7, 10.0 and 16.7%, respectively) at the end of the storage period (Table 3). Sprouting was inhibited with CIPC, spearmint EO and S-(+)-carvone treatments for 120 days and dill EO treatments for 135 days in the tubers stored at 10 °C. At 10 °C storage, the control tubers sprouted on the 60th day of storage and the sprouting was 100% at the 165th day (Fig. 1). CIPC-treated tubers showed 5.7% sprouting, while dill EO-treated tubers showed 16.7% sprouting, and spearmint EO and S-(+)-carvone-treated tubers showed more than 30% sprouting at the end of the storage period (Table 3). Dill EO and CIPC treatments effectively suppressed sprouting of tubers stored at 15 °C, and less than 20% of tubers sprouted at the end of the storage period. Spearmint EO and S-(+)-carvone caused a limited sprout inhibition at high temperature storage, and nearly all tubers sprouted during the last days of

Table 2 Mean sprout suppression effects of treatments. The unit of mean sprout suppression effect is 1-7 scale (Hartmans et al. 1995)

Treatments	Storage temperature (°C)			
	5	10	15	Mean
Caraway EO	7.0	7.0	7.0	7.0a
Spearmint EO	5.7	3.7	1.5	3.6c
Dill EO	6.5	5.7	5.0	5.7b
S-(+)-carvone	5.3	3.5	1.7	3.5c
CIPC	6.5	5.8	5.0	5.8b
Control	2.8	1.2	1.0	1.7d
Mean	5.6a	4.5b	3.5c	
$LSD_{int.}$	0.32**			

Mean values with different lowercase letters in the same column differ significantly according to Duncan's test ($P \leq 0.05$)

LSD least significant difference

**$P < 0.01$

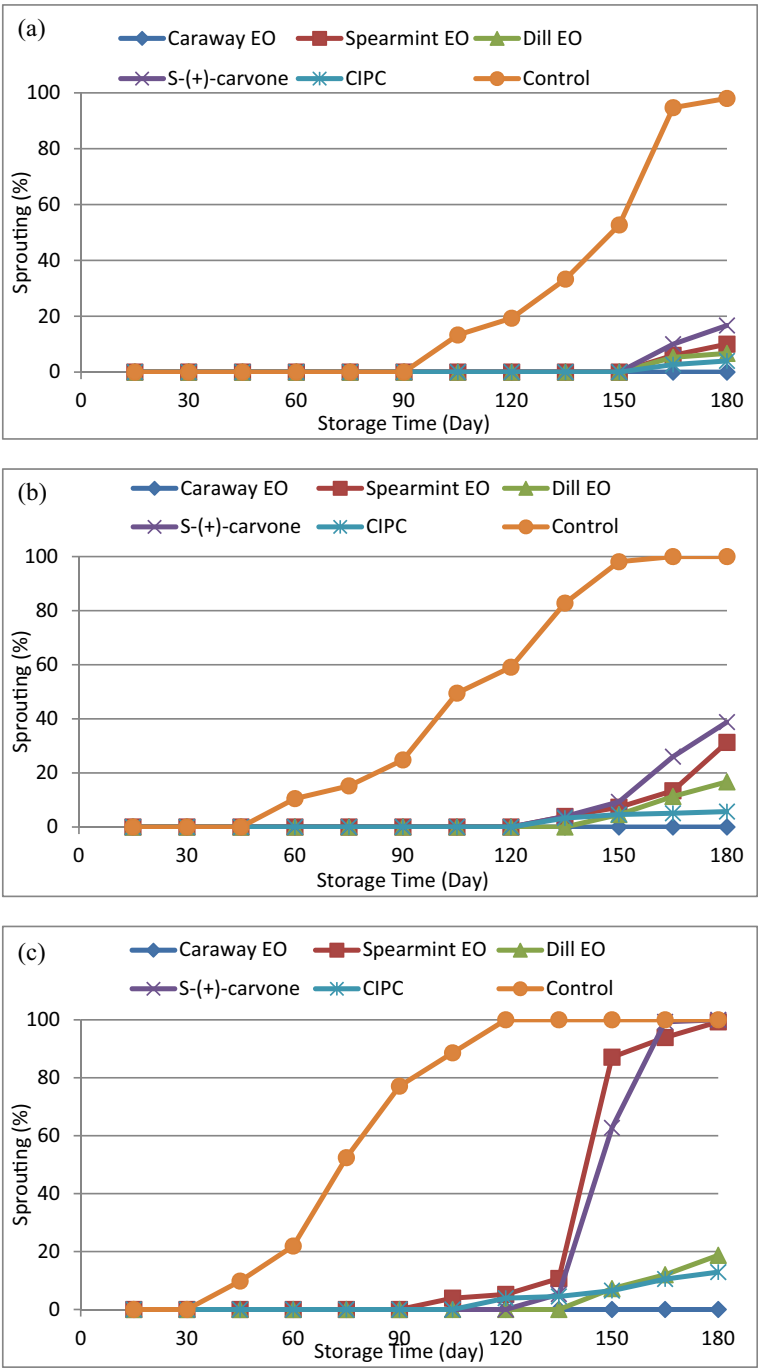

Fig. 1 Sprouting (%) of potato tubers treated with essential oils, S-(+)-carvone, CIPC, and controls during 180 days of storage at different temperatures. (**a**) 5 °C. (**b**) 10 °C. (**c**) 15 °C

Table 3 Effect of caraway, spearmint and dill EOs, S-(+)-carvone and CIPC treatments on sprouting, sprout length and weight loss in potato tubers after 6 months storage at different temperatures

Treatments/	Sprouting (%)			Sprout length (mm)			Weight loss (%)		
Temperature	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C	5 °C	10 °C	15 °C
Caraway EO	0.0	0.0	0.0	0.0	0.0	0.0	3.8	5.6	6.8
Spearmint EO	10.0	31.3	99.3	2.0	9.6	14.3	4.4	7.5	9.0
Dill EO	6.7	16.7	18.7	2.0	3.6	3.6	4.1	6.4	7.7
S-(+)-carvone	16.7	38.8	100	3.4	4.6	7.5	4.5	8.3	10.6
CIPC	4.0	5.7	12.9	2.0	2.0	2.0	4.3	6.8	9.9
Control	98.0	100	100	11.7	19.2	33.9	6.1	10.4	13.4
CV	5.72			6.44			4.48		
$LSD_{int.}$	3.47**			0.72**			0.64**		

CV coefficient of variation, *LSD* least significant differences

**$P < 0.01$

storage. Non-treated tubers sprouted after 45 days of storage, and dormancy was broken in 100% of tubers after 120 days of storage (Fig. 1).

Sprout Length

Although dormancy was broken at different periods of storage in CIPC-treated tubers, sprout length did not exceed 2 mm in these tubers at the end of the storage period for all storage conditions (Fig. 2). Due to early break of dormancy in control tubers, sprout length increased during storage period and at the end was 11.7, 19.2 and 33.9 mm at 5, 10 and 15 °C storage temperatures, respectively (Table 3). The sprout length of S-(+)-carvone treated tubers stored at 5 °C was 3.4 mm, which was higher than those of CIPC, dill EO and spearmint EO-treated tubers whose sprout length did not exceed 2 mm (Table 3). While dormancy was broken at the same period of storage in S-(+)-carvone and spearmint EO treatments, sprout length was higher in the tubers treated with spearmint EO (9.6 mm) than those treated with S-(+)-carvone (4.6 mm) and dill EO (3.6 mm) at the end of the storage period at 10 °C (Table 3). Sprout length was nearly twofold higher for the tubers treated with spearmint EO (14.3 mm) as compared to those treated with S-(+)-carvone (7.5 mm) at 15 °C. At the same temperature, the sprout length of dill EO treated tubers was even lower (3.6 mm) (Table 3).

Weight Loss

The effects of treatments on weight loss were similar until the 90th, 60th and 45th days of storage at 5, 10 and 15 °C, respectively. Significant changes were observed after these periods. All treatments significantly decreased weight losses as compared to the control. At the end of the storage period, the highest weight loss was observed for non-treated tubers at all storage temperatures (6.1, 10.4 and 13.4%, respectively) (Table 3). The changes in weight loss at the end of the storage period were between 3.8 and 6.1% for the tubers stored at 5 °C, but the differences between treatments were not statistically

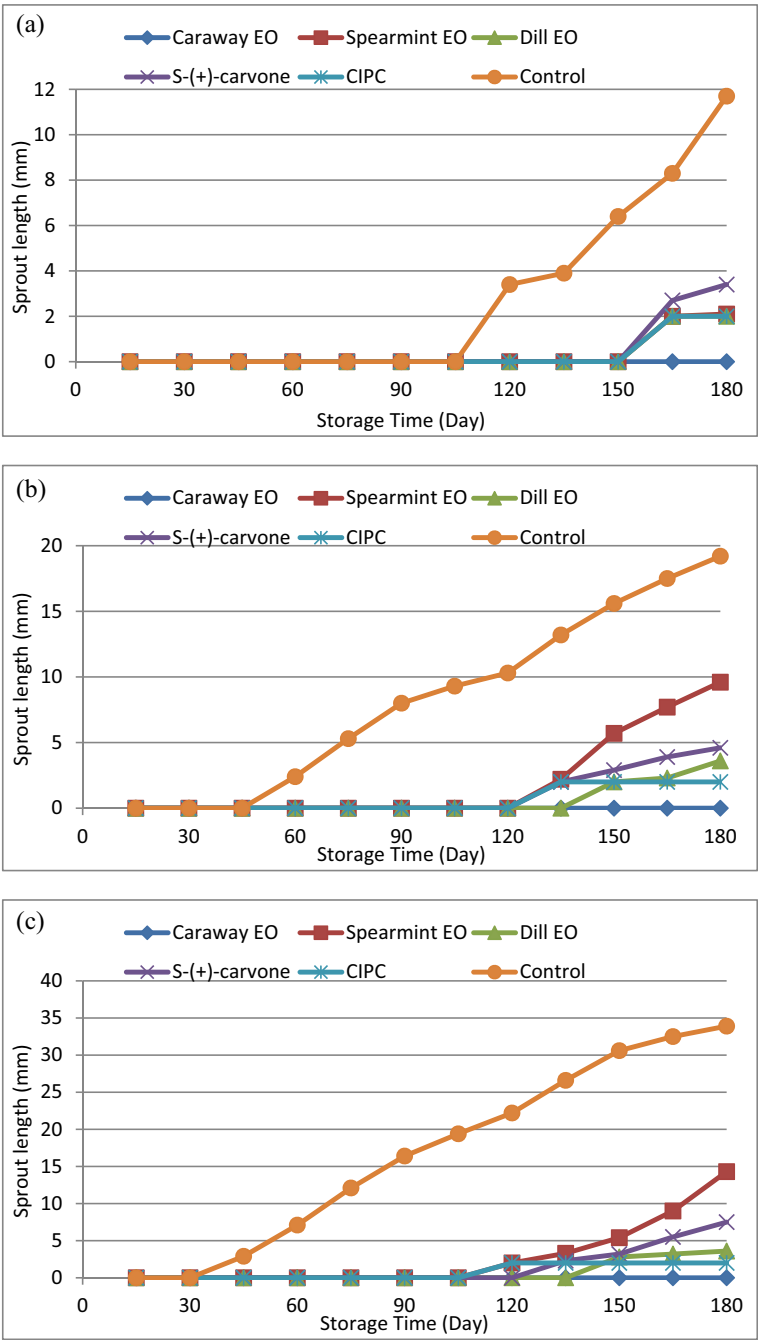

Fig. 2 Sprout length (mm) of potato tubers treated with essential oils, S-(+)-carvone, CIPC, and controls during 180 days of storage at different temperatures. (**a**) 5 °C. (**b**) 10 °C. (**c**) 15 °C

significant, apart from being different from that of the control (Table 3). The most effective treatment for preventing weight loss was also caraway EO treatment at 10 (5.6%) and

15 °C (6.8%) storage conditions. While EO- and CIPC-treated tubers had similar weight losses (3.6–4.0%) until the 135th day of storage at 10 °C, the increase in weight loss was higher in spearmint EO treatments towards the end of the storage period (Fig. 3). After 90 days of storage, the S-(+)-carvone treatments caused higher weight loss than the other treatments at 10 °C. The weight loss of tubers treated with S-(+)-carvone and CIPC from 60th day to the end of the storage was higher than that of the EO-treated tubers at 15 °C. At 15 °C, the effects of EOs on weight losses were similar until 105th day of storage, after which the observed weight losses changed depending on the sprout inhibitory effects of treatments (Fig. 3). The weight loss was 7.7% for dill EO, showing potent sprout inhibitory effect, and the weight loss was 10.6% for S-(+)-carvone, demonstrating moderate sprout inhibitory effect at the end of the storage period (Table 3). While sprouting was inhibited substantially with CIPC treatments, the weight loss of CIPC treated tubers was higher than that of EO-treated tubers, especially at higher temperatures.

Efficacy Degree of Sprouting

Sprouting was strongly influenced by the storage temperature, increasing with the increase in storage temperature in the present study. All treatments were able to suppress sprout growth. The best result was achieved with caraway EO treatments. Caraway EO presented the most efficient sprout inhibitory effect even at higher storage temperatures. Dill EO and CIPC treatments also had very efficient sprout suppression, but their effects started to decrease at high temperatures. Sprout suppressing effects of spearmint EO and S-(+)-carvone were very high at 5 °C, but their effects significantly decreased with increased storage temperature (Table 2).

Residue Levels (mg/kg fw)

The carvone residue levels varied between 2.24 and 11.11 ppm in peelings and between 0.40 and 4.31 ppm in peeled tubers. Carvone residues in peelings and peeled tubers significantly decreased with increasing storage temperature (Table 4). The changes in carvone residue levels of peelings and peeled tubers with storage temperature were similar for all EO treatments. For all storage temperatures, carvone residue found in peelings of S-(+)-carvone-treated tubers (11.11, 6.89 and 3.62 ppm for 5, 10 and 15 °C, respectively) was higher than that in the EO treated tubers (Table 4). Carvone residue in peeled tubers was similar for S-(+)-carvone and EO treatments at 5 °C (4.03–4.31 ppm) and 15 °C (0.40–0.46 ppm), but more carvone residue was found with S-(+)-carvone treatments at 10 °C (2.39 ppm) than EO-treated tubers at same temperature (Table 4). The residue of CIPC in peelings significantly decreased with increasing storage temperatures and was found to be 16.0, 10.9 and 5.2 ppm at 5, 10 and 15 °C, respectively (Table 5).

Discussion

Sprout Suppression

As found in this study, many researchers have reported that CIPC has strong inhibitory effects on potato sprouting (Fraizer et al. 2004; Afek et al. 2000; Mehta et al. 2010; Lu

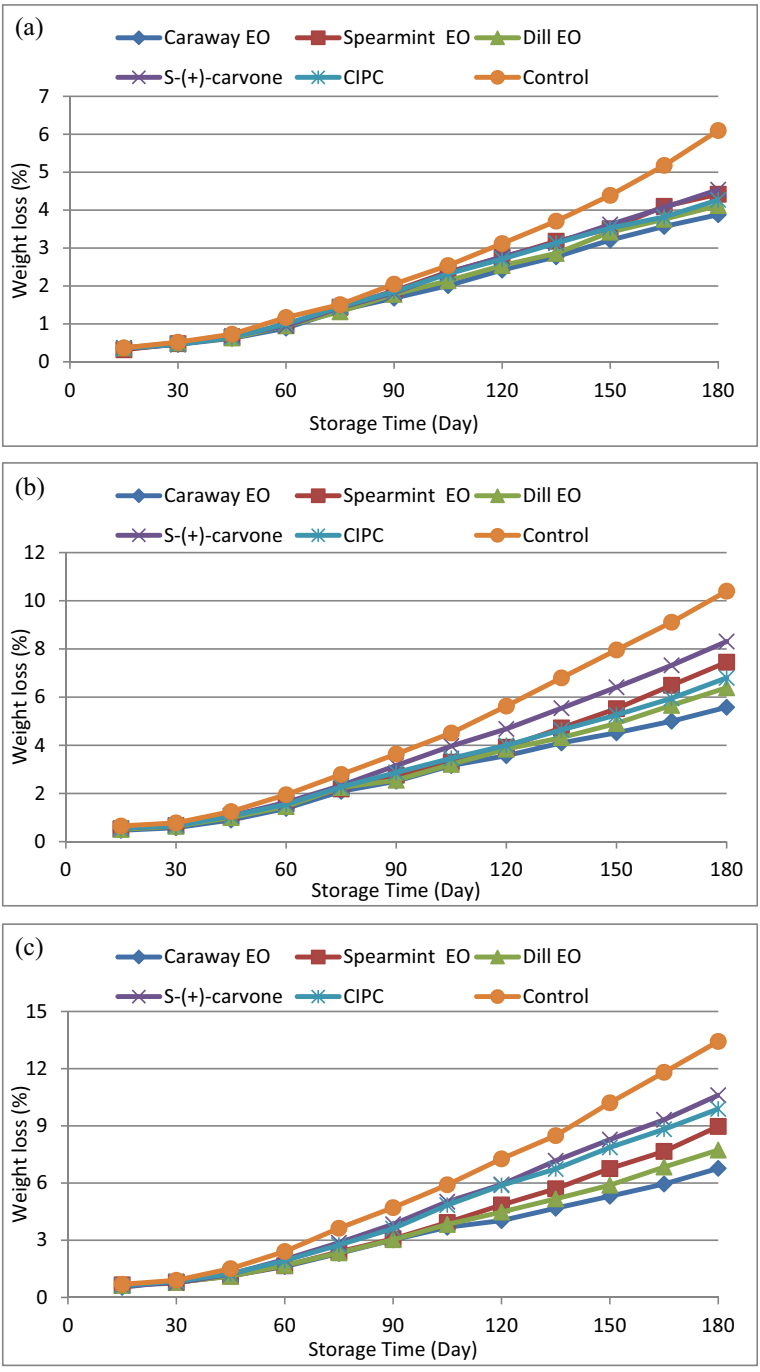

Fig. 3 Weight loss (%) of potato tubers treated with essential oils, S-(+)-carvone, CIPC, and controls during 180 days of storage at different temperatures. (**a**) 5 °C. (**b**) 10 °C. (**c**) 15 °C

Table 4 Carvone residue levels (ppm) in peelings and peeled tubers after 6 months storage at different temperatures

Treatments/	Peelings				Peeled tubers			
Temperature	5 °C	10 °C	15 °C	Mean	5 °C	10 °C	15 °C	Mean
Caraway EO	7.80	3.98	2.25	4.67b	4.13	1.07	0.40	1.87b
Spearmint EO	8.67	3.67	2.63	5.00b	4.20	1.30	0.42	1.97b
Dill EO	9.32	3.21	2.24	4.92b	4.03	1.11	0.40	1.85b
S-(+)-carvone	11.11	6.89	3.62	7.21a	4.31	2.39	0.46	2.39a
Mean	9.23a	4.44b	2.68c		4.17a	1.47b	0.42c	
CV	9.80				12.50			
$LSD_{int.}$	0.90**				0.43**			

Mean values with different lowercase letters in the same column differ significantly according to Duncan's test ($P \leq 0.05$)

CV coefficient of variation, *LSD* least significant differences

**$P < 0.01$

et al. 2011; Saraiva and Rodrigues 2011). CIPC inhibits sprouting by interfering with mitotic cell division. It interrupts the spindle formation and permanently damages the tuber buds (Nurit et al. 1989; Kleinkopf et al. 2003). CIPC spray is often applied to potatoes that have already received one or two CIPC aerosol treatments, to ensure that the tubers remain sprout free during transportation and fresh market utilization (Kerstholt et al. 1997). Also, as found in this study, plants rich in carvone have been reported to suppress sprouting: for example, caraway (Cizkova et al. 2000; Silva et al. 2007; Şanlı et al. 2010), spearmint (Fraizer et al. 2004; Song et al. 2004; Elsadr and Waterer 2005) and dill (Song et al. 2004; Gomez et al. 2010). Furthermore, as found in this study, it was reported that some EOs containing carvone were more effective than CIPC or pure S-(+)-carvone in reducing potato sprouting (Cizkova et al. 2000; Elsadr and Waterer 2005). In this study, essential oil applications were adjusted so that the total amount of carvone applied was the same. Therefore, it is considered that the other compounds present in EO (e.g. limonene) individually or by interacting with each other also affected sprout inhibition. As Carvone and limonene were the major compounds

Table 5 CIPC residue level (ppm) in peelings after 6 months storage at different temperatures

Treatments/	Peelings		
Temperature	5 °C	10 °C	15 °C
CIPC	16.0a	10.9b	5.2c
CV (%)	7.74		

Mean values with different lowercase letters in the same column differ significantly according to Duncan's test ($P \leq 0.05$)

CV coefficient of variation

contained in the caraway and dill EOs, the additional sprout suppression response was likely due to the synergistic effect of these two compounds.

Sprout suppressing ability of spearmint EO and S-(+)-carvone significantly decreased with increasing storage temperature, while caraway and dill EO inhibited sprouting very effectively even at high temperatures. Spearmint EO treatments were not as effective as caraway and dill oil treatments at suppressing sprouting in treated tubers, most likely due to the composition of oils. Caraway and dill oils contain S-(+)-carvone isomer, while spearmint oil contains the R-(-)-carvone isomer. Oosterhaven (1995) reported that the sprout inhibition ability of S-(+)-carvone was more potent than that of R-(-)-carvone. Although the physical properties of the two compounds are very similar, including the molecular weight, solubility and volatility, their interactions with phospholipid monolayers and peptides have been reported to be different (Pathirana et al. 1992; Nandi 2005).

In this study, essential oil application using wick system at regular intervals probably slowed the rapid release of the EOs, thus prolonging their sprout inhibition ability. Carvone, particularly S-(+)-carvone, has been shown to be effective in suppressing sprouting both in small- and large-scale studies with different apparatuses (Hartmans et al. 1995; Oosterhaven 1995; Silva et al. 2007). Treatments should ensure a low and constant carvone concentration around the tubers, and repeated applications are necessary for achieving effective sprout suppression for a long-term storage (Kleinkopf et al. 2003; Fraizer et al. 2004). Hartmans et al. (1995) also reported that carvone was able to suppress sprouting during the whole storage period and that applications done every 6 weeks resulted in a better sprout suppressing effect than the standard CIPC treatment.

Sprout Length

The differences between the treatments in terms of sprout length were closely associated with their sprout inhibition effects, and sprout length was longer in earlier sprouted tubers. However, the limited elongation of sprouts of dill EO-treated tubers could be due to the sprouting inhibitory effects of dill EO persisting even after the breaking of dormancy. It was reported that the length of sprouts was based on the effectiveness of treatments used for extending the duration of dormancy (Elsadr and Waterer 2005; Frazier et al. 2006; Silva et al. 2007; Owolabi et al. 2013).

Weight Loss

The mobilization and transport of carbohydrates and other nutrients from the storage parenchyma tissue into the growing buds cause weight losses (Fernie and Willmitzer 2001). The sprouting of potato tubers during post-harvest storage results in a considerable increase in the total weight loss of tubers. Since sprouting was effectively suppressed with caraway and dill EO treatments, weight loss was much lower in these treatments. Sprouted tubers lose weight more than unsprouted tubers since sprouting increases the surface area for water loss (Singh et al. 2004). Different studies consistently reported that the major compounds contained in certain EOs, such as S-(+)-carvone, R-(−)-carvone and limonene decreased weight loss by suppressing both sprouting and fungal growth during storage (Vaughn and Spencer 1991; Vokou et al. 1993; Hartmans et al. 1995; Oosterhaven 1995;

Bandara et al. 2003; Şanlı et al. 2010). Hence, increased weight loss may be partly due to tuber infection with fungal and bacterial diseases, particularly dry rot and soft rot. In this study, rotting also caused weight loss in the control and CIPC-treated tubers as well as evaporation, respiration and sprouting. No rotting was observed in the essential oil-treated tubers (data not shown).

Residue Levels

Decreasing carvone residue levels with increasing storage temperature can be explained by the faster evaporation of the carvone at higher temperatures. The reason why carvone residues in the peelings were higher as compared to peeled tubers was probably due to the adsorption of most carvone at the suberized potato periderm. Hartmans et al. (1995) showed a rapid decrease in carvone residue level at the end of the storage period due to increased ventilation. However, carvone residue level could be more than 20 ppm when applied at 100 ml/1000 kg tuber. The same researches showed that the majority of the carvone residue was found in the potato peel and less than 1% of carvone was found inside the potato. A plant-derived compound can be applied on certified organic crops and is expected to leave behind little or no residue, because of its high volatility (Hartmans et al. 1995). Similar results were also found by Oosterhaven (1995), reporting that the accumulation of S-carvone in potato tissue was dependent on the type of tissue used, with carvone residue levels of less than 1 ppm in peeled potato tuber, 10 ppm in peels and 20 ppm in sprouts.

MRLs of CIPC of 10 and 30 mg/kg of tubers are recommended by the European Union and the US Environmental Protection Agency, respectively (Kleinkopf et al. 2003; EPA 2012). In this study, the CIPC residues in peelings were above permissible limits of the European Union with the exception of tubers stored at 15 °C. CIPC residue levels can vary amongst potato tubers and are influenced by a number of factors related to the application of CIPC in the potato storage, such as storage temperature, application methods and dose, storage time and formulation type. CIPC residues were found to be significantly higher in potato peel stored at low temperature as compared to the potatoes stored at high temperature (Ezekiel and Singh 2007; Singh and Ezekiel 2010). Observed differences can be explained by the relatively volatile nature of CIPC at higher temperatures. Wilson et al. (1981) observed residues of 45 mg/kg following aerosol treatment, whereas a study by Mondy et al. (1992) showed that potato tubers dipped in a 1% emulsion of CIPC resulted in residues of up to 400 mg/kg in the peel. CIPC concentrations ranged from 5.47 immediately after CIPC application to 0.76 ppm 202 days after storage (Lewis et al. 1997).

Conclusion

Carvone containing essential oils (EOs) were effective in suppressing sprout growth of potato cultivar Agria under storage temperatures ranging from 5 to 15 °C. Amongst EOs, the most effective one was caraway EO, which was superior to CIPC application, by completely suppressing sprouting throughout the 6-month period, even under 15 °C storage temperature. Dill EOs also significantly suppressed sprouting, and their effect was equivalent to CIPC, while spearmint EO and S-(+)-carvone exhibited a limited

sprout suppressing effect at high storage temperatures. EOs leave behind little or no residue as they are highly volatile. The application of EOs is recommended to be repeated periodically or on a continuous basis since new sprouts continue to grow. A wick application of EOs provided high efficacy through a frequent low concentration. EO treatments continued to retard sprout growth well after the source chemicals were removed. This suggests that these treatments could be used to suppress the sprouting of seed potatoes. The use of caraway and dill seed EOs shows promise as a replacement for CIPC in prolonging potato storage. These EOs are readily available and inexpensive with a long history of safe use. Hence, this single year study should be extended to provide more detailed recommendations for their use.

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