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Screening of Plant Essential Oils as Potato Sprout Suppressants at Low Storage Temperature

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Abstract
Sprouting of potatoes during storage could result in general quality losses, including weight and nutrient losses. In this work, potato tubers were treated with 18 kinds of plant essential oils during a storage period of 270 days at low temperature (3 ± 0.5 °C), and at the end of the storage period, the sprout inhibition effect, starch and reducing sugar contents were assessed. Results showed that citronella (*Cymbopogon nardus*) essential oil, wintergreen (*Ilex chinensis* Sims) essential oil, DL-menthol, jasmine (*Jasminum sambac*) essential oil, citral and nerol had a better sprouting control than that of CIPC (isopropyl N-(3-chlorophenyl) carbamate). Raspberry ketone was found to promote potato sprouting; the sprout length reached 5 cm at 270 days, whilst the control was 1.7 cm. On the other hand, the potatoes treated with 100 μL/L of citronella essential oil and wintergreen essential oil did not sprout, whilst the sprouting rate and sprouting index of the control were 73.33% and 23.81%, respectively. At the end of storage, the starch content of potato tubers treated with citronella essential oil and wintergreen essential oil were maintained at 15.32% and 15.80%, respectively, which was higher than that of the control (14.14%). On the contrary, the reducing sugar content of potato tubers treated with the above two essential oils were 1.28% and 1.24%, respectively, which was lower than that of the control (1.47%). These results suggest that citronella essential oil and wintergreen essential oil treatments reduced starch breakdown and reducing sugar accumulation. Therefore, citronella essential oil and wintergreen essential oil could be considered as new sprout suppressants for potato storage. Further work needs to be done at higher temperatures (8–12 °C) to confirm their effectiveness.

Keywords Essential oil · Potato tuber · Sprouting · Sprout suppressants

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Introduction

Potato (*Solanum tuberosum* L.) is the world's largest non-grain food crop, with global potato production exceeding 300 M tons every year (Gumbo et al. 2021). At a time when the world is facing food shortages and population growth, the Food and Agriculture Organization (FAO) endorses the classification of potato as a food security crop (Devaux et al. 2020). Besides, potato is the 4th major food crop in China. Normally, potato tubers lie dormant at harvest time; after dormancy, they begin to sprout with a series of physiological and biochemical changes. Potato tuber sprouting is one of the biggest problems in the postharvest storage and transportation (Huang et al. 2022), as it reduces tuber quality causing weight losses and shrinkage (Visse-Mansiaux et al. 2021). When used for direct consumption or processing, tubers need to be stored in the absence of light to avoid the synthesis of solanine and chaconine, which cause nausea, headache, coma, and other symptoms if consumed in excess (Noureddine 2019). Additionally, sprouting reduces the tuber's quality by converting starch into reducing sugar (Sorce et al. 2005). Hence, for fresh edible and processed potato tubers, it is critical to inhibit sprout growth and prolong storage time after harvest.

At present, the long-term storage conditions of ware potato require 2–4 °C to inhibit tuber sprouting. However, long-term preservation at low temperatures induces cold-sweetness (Sowokinos 2007), and the increase of reducing sugar content in potato tubers results in blackening of colour during frying, which reduces potato processing quality seriously. Besides low-temperature storage, spraying, fumigation, or soaking of sprout suppressants could also effectively inhibit potato tuber sprouting (Gumbo et al. 2021). Isopropyl N-(3-chlorophenyl) carbamate (CIPC) is the most commonly used chemical sprout suppressant in potato storage, but it has been proven to be detrimental to the environment and human health (Vijay et al. 2018). It is reported that the CIPC residual amounts in potato epidermis were about 15–85 mg/kg (Bhattacharya et al. 2021). Because the degradation product of CIPC is highly carcinogenic and toxic to the environment, it has been banned by the European Union (Paul et al. 2016), and the minimum residual amount of CIPC is limited to 30 mg/kg in China. Therefore, it is urgent to develop new sprout suppressants that are safe for humans and friendly to the environment to replace chemical sprout suppressants, and some researchers are constantly exploring the technology to control potato tuber sprouting.

Essential oils as natural plant products extracted by steam distillation or other solvents (Ban et al. 2020) have attracted more attention from researchers in controlling potato tuber sprouting. Studies have found that the main components of essential oils are terpenoids and phenylpropanoids (Raut and Karuppayil 2014); many of which have biological and pharmacological effects, such as antibacterial, antiviral, and antioxidant activities (Adorjan and Buchbauer 2010). In terms of controlling potato sprouting, Şanlı et al. (2019) reported that caraway (*Carum carvi* L.) essential oil, dill (*Anethum graveolens* L.) essential oil, spearmint (*Mentha spicata* L.) essential oil, and S-(+)-carvone could effectively prolong the storage period of potato, and inhibited potato tuber sprouting for more than 120 days (Şanlı et al. 2019).

Finger et al. (2018) showed that eugenol and menthol could not only effectively reduce potato tuber sprouting rate, but also prevent plant pathological damage. In addition, Coleman et al. (2001) treated potato tubers with menthone and menthol under dark conditions and found that the inhibitory efficiency of the mixture was 5–10 times higher than that of S-(+)-carvone.

Although the use of essential oils to control potato tuber sprouting is considered as a potential alternative to sprout suppressants, there are few studies comparing the sprout inhibition effects of different plant essential oils and their main components. In practical application, high concentration of plant essential oil may adversely affect the quality of potato. However, there are few reports on determining the appropriate dosage of essential oils. Therefore, this study aimed to systematically evaluate the inhibitory effects of 18 kinds of plant essential oils on potato sprouting during 270 days of storage at low temperature (3 ± 0.5 °C). Three kinds of chemical sprout suppressants (chlorine dioxide, exogenous ethylene, CIPC) were selected as positive treatments; 18 kinds of plant essential oils including citronella (*Cymbopogon nardus*) essential oil, wintergreen (*Ilex chinensis Sims*) essential oil, peppermint (*Mentha piperita* L.) essential oil, spearmint (*Mentha spicata* L.) essential oil, lemon (*Citrus limon* L.) essential oil, clove (*Syzygium aromaticum* L.) essential oil, jasmine (*Jasminum sambac*) essential oil, cinnamon (*Cinnamon cassia*) essential oil, perilla (*Perilla frutescens*) essential oil, citral, geraniol, nerol, eugenol, cinnamaldehyde, DL-menthol, S-(+)-carvone, ionone, and raspberry ketone were tested. The effects of different treatments on the sprouting rate, sprouting index, sprouting morphology, reducing sugar, and starch content of potato tuber were determined.

Materials and Method

Materials

Potato tubers of the cultivar “Favorita” were purchased from a local market (Zibo City, Shandong Province, China) in July 2021 for all experiments. After the potato tubers were transported to the laboratory, they were left in the dark for 7 days, then uniformly sized (100 ± 20 g/tuber) with no mechanical damage, and with absence of pests and diseases were selected. For each of the three replications used in the study, 2 kg of potatoes was placed in plastic baskets (10-L capacity). The different treatments are described in Table 1.

Potato Tuber Treatments and Sampling

In our study, 18 kinds of plant essential oils and 3 kinds of chemical sprout suppressants were selected to inhibit potato sprouting. Potato tubers were treated at room temperature and then quickly transferred to cold storage shelf for 270 days at low temperature (3 ± 0.5 °C). To avoid interaction between essential oils, potatoes treated with the same essential oil were placed on the same shelf. Four

Table 1 Details of essential oils and other sprout suppressants used in the experiment

Reagent	Purity	CAS no.	Source of reagent
Ionone	92%	127-41-3	Jishui Jianmin Natural spice Oil Co., Ltd. (Jian City, China)
Citral	97%	5392-40-5	
Cinnamaldehyde	99%	104-55-2	
Geraniol	97%	106-24-1	
Nerol	98%	106-25-2	
Eugenol	99%	97-53-0	
DL-menthol	99%	1490-04-6	
Raspberry ketone	99%	5471-51-2	
Citronella essential oil	99%	91771-61-8	Chongqing Fangdai Cosmetics Co., Ltd. (Chongqing City, China)
Wintergreen essential oil	99%	68917-75-9	
Peppermint essential oil	99%	8006-90-4	
Spearmint essential oil	99%	8008-79-5	
Lemon essential oil	99%	8008-56-8	
Clove essential oil	99%	8000-34-8	
Jasmine essential oil	99%	8022-96-6	
Cinnamon essential oil	99%	8007-80-5	
Perilla essential oil	99%	68132-21-8	
S-(+)-carvone	97%	2244-16-8	Shanghai Maclin Biochemical Technology Co., Ltd. (Shanghai City, China)
Chlorine dioxide	8%	10049-04-4	Beijing Hualong Xingyu Technology Development Co., Ltd. (Beijing City, China)
Exogenous ethylene	20%	74-85-1	Shandong Awett Biotechnology Co., Ltd. (Jinan City, China)
Isopropyl N-(3-chlorophenyl) carbamate (CIPC)	99%	101-21-3	Hubei Qifei Pharmaceutical and Chemical Co., Ltd. (Tianmen City, China)

concentrations were set for 18 kinds of plant essential oils and chlorine dioxide treatment, two concentrations for exogenous ethylene, and one concentration for CIPC. At the same time, the potatoes without any treatment were used as the control. There were 80 treatments in the experiment, and each treatment was repeated three times (Table 2). There were three experimental treatment methods: (1) plant essential oils, such as citronella essential oil, wintergreen essential oil, peppermint essential oil, lemon essential oil, clove essential oil, jasmine essential oil, cinnamon essential oil, perilla essential oil, geraniol, nerol, eugenol, cinnamaldehyde, S-(+)-carvone, and ionone, were added to filter paper, which was attached to a plastic basket for airtight fumigation (treatment concentration was calculated based on the volume of the basket); (2) chemical sprout suppressants, such as exogenous ethylene and chlorine dioxide. Exogenous ethylene solid release agent (93.7 μL/L or 199.3 μL/L final released gas concentration) and chlorine dioxide sustained release agent were placed in a Petri dish, a small amount of water was added, and then placed in a plastic basket with potatoes for airtight fumigation; (3) solid matter, such as CIPC, DL-menthol, and raspberry ketone. CIPC application methods mainly include powder/dust application, aerosol, and dip treatment (Singh and Ezekiel 2010). Amongst them, powder/dust application is the most widely convenient method of CIPC application. Therefore, in this experiment, a certain amount of CIPC was mixed with sterilized

Table 2 Concentrations of 18 kinds of plant essential oils and 3 kinds of chemical sprout suppressants

Order	Reagent	Treatment dose
1	CK	0
2	Citronella essential oil	20, 50, 100, 200 μL/L
3	Wintergreen essential oil	20, 50, 100, 200 μL/L
4	Peppermint essential oil	20, 50, 100, 200 μL/L
5	Spearmint essential oil	20, 50, 100, 200 μL/L
6	Lemon essential oil	20, 50, 100, 200 μL/L
7	Clove essential oil	20, 50, 100, 200 μL/L
8	Jasmine essential oil	20, 50, 100, 200 μL/L
9	Cinnamon essential oil	20, 50, 100, 200 μL/L
10	Perilla essential oil	20, 50, 100, 200 μL/L
11	Citral	20, 50, 100, 200 μL/L
12	Geraniol	20, 50, 100, 200 μL/L
13	Nerol	20, 50, 100, 200 μL/L
14	Eugenol	20, 50, 100, 200 μL/L
15	Cinnamaldehyde	20, 50, 100, 200 μL/L
16	S-(+)-carvone	20, 50, 100, 200 μL/L
17	Ionone	20, 50, 100, 200 μL/L
18	Exogenous ethylene	93.7, 199.3 μL/L
19	Chlorine dioxide	10, 20, 40, 80 mg/kg
20	DL-menthol	0.3, 0.75, 1.5, 3.0 g/kg
21	Raspberry ketone	0.3, 0.75, 1.5, 3.0 g/kg
22	2.5% CIPC	0.8 g/kg

soil and evenly scattered on the potatoes. DL-menthol and raspberry ketone are solid, so they are treated in the same way as CIPC. The treatment concentrations of chlorine dioxide, DL-menthol, raspberry ketone, and CIPC were calculated based on the weight of potatoes per basket.

Sprouting rate, sprouting index, and quality index, such as starch and reducing sugar content of potatoes by selected essential oils, were measured at 180 days and 270 days. At 180 days and 270 days of storage, three potatoes were randomly selected from each treatment and sampled twice from the top to the bottom of potato tubers with a puncher, and then sampled twice more perpendicular to the above direction. The shape of the puncher was 1 cm × 10 cm (diameter × length), and the samples with a diameter of 1 cm taken by the puncher were cut into slices with a thickness of about 3 mm. Then the potato sample was ground into powder and stored at −80 °C, for the determination of quality such as starch and reducing sugar contents.

Determination of Sprouting Rate and Sprouting Index

Five potatoes were randomly selected from each treatment, and the number and grade of potato sprouting were recorded, respectively. The classification standards of potato tuber sprouting are as follows: level 0 = sprouts ≤ 2 mm, level 1 = sprouts > 2 to ≤ 5 mm, level 2 = sprouts > 5 to ≤ 10 mm, level 3 = sprouts > 10 to ≤ 15 mm, level 4 = sprouts > 15 to ≤ 20 mm, level 5 = sprouts > 20 to ≤ 25 mm, level 6 = sprouts > 25 to ≤ 30 mm, and level 7 = sprouts ≥ 30 mm. When the potato sprout length was less than or equal to 2 mm, it was regarded as not sprouting or in sprouting state; when the potato sprout length was greater than 2 mm, it was regarded as sprouted. The sprouting rate and sprouting index were calculated according to the following equation:

$$Sprouting\ rate\ (\%) = \frac{no.\ of\ sprouted\ tubers}{total\ no.\ of\ tubers} \times 100 \tag{1}$$

$$Sprouting\ index\ (\%) = \frac{\sum (amount \times level)}{5 \times 7} \times 100 \tag{2}$$

where 5 is the number of potatoes selected each time and 7 is the highest level of sprouting.

The Sprouting Morphology of Potato Tubers with Essential Oil Treatments

At the end of the storage period (270 days), it was observed that the sprouting inhibition effect of citronella essential oil and wintergreen essential oil was the most significant. Therefore, four potato tubers were taken from each treatment for photographing, and the sprouting morphology of the two essential oil-treated and untreated potatoes was compared. The potatoes were placed in the camera box and photographed from the top of the camera box. The shape of the camera box wa 60 cm × 60 cm × 60 cm (length × width × height), and the photographic distance was 60 cm.

Determination of Reducing Sugar Content

The reducing sugar content was determined according to Kapoor et al. (2020), which was estimated using the DNS reagent. Two grams of potato tubers per replication was mixed with 30 mL distilled water and then placed in 80 °C water bath for 20 min. Two milliliters of DNS reagent was added to 1 mL of the extract. The absorbance of the solution was recorded at a wavelength of 540 nm by UV-Vis spectrophotometer. The reducing sugar content was obtained using an appropriate calibration curve ($y = 0.8985x + 0.0161$, $R^2 = 0.9991$). The amount of reducing sugar was expressed as the percentage of reducing sugar in tubers.

Determination of Starch Content

The determination of starch content was based on the method of Men and Liu (1995), with some modifications. Two grams of potato tubers per replication was mixed with 30 mL petroleum ether and 30 mL 80% (v/v) ethanol solution and filtered. The filter residue was placed in a beaker and heated continuously in a boiling water bath until the starch was completely gelatinized into a transparent solution. The absorbance was measured at a wavelength of 660 nm, and the calibration curve of soluble starch was obtained with the equation $y = 0.001x + 0.0033$, $R^2 = 0.9990$.

Statistical Analysis

Results were analysed by the SPSS software (25.0, IBM, Armonk, NY, USA) at a significance level <0.05.

Results and Discussion

Sprout Suppression Capacity of Different Compounds

Potato tubers in all treatments and the control were stored on cold storage shelf at 3 ± 0.5 °C. The mentioned plant essential oils and chemical sprout suppressants were performed for potato tuber sprouting inhibition experiment, and the experimental results are shown in Table 3. During 270 days of storage, potato tubers treated with 100 μL/L wintergreen essential oil, citronella essential oil, jasmine essential oil, citral, and nerol treatments did not sprout, whilst the sprouting rate and sprouting index of the control were 73.33% and 23.81%, respectively. As the positive treatment, 800-mg/kg CIPC treatment completely inhibited the potato tuber sprouting after 180 days of storage, but after 270 days, the sprouting rate and sprouting index were 2.22% and 0.95%, respectively. The sprouting rate and sprouting index of potato treated with 80 mg/kg chlorine dioxide at 270 days were significantly lower than that of the control, which were

Table 3 Sprouting inhibition efficiency of 18 kinds of plant essential oils and 3 kinds of chemical sprout suppressants

ReagentTreatment dose		Sprouting rate (%)		Sprouting index (%)	
		180 days	270 days	180 days	270 days
Control	0	17.80 ±7.70	73.33 ± 13.33	1.90 ± 1.65	23.81 ± 9.45
Citronella essential oil	20 μL/L	4.44 ± 3.85	8.89 ± 3.85	1.90 ± 1.65	10.48 ± 3.30
	50 μL/L	8.89 ± 10.18	8.89 ± 3.85	2.86 ± 2.86	7.62 ± 1.65
	100 μL/L	0	0	0	0
	200 μL/L	0	0	0	0
Wintergreen essential oil	20 μL/L	2.22 ± 3.85	15.56 ± 7.70	0.95 ± 1.65	3.81 ± 1.65
	50 μL/L	4.44 ± 3.85	8.89 ± 7.70	1.90 ± 1.65	2.86 ± 2.86
	100 μL/L	0	0	0	0
	200 μL/L	0	0	0	0
Peppermint essential oil	20 μL/L	6.67 ± 6.67	17.78 ± 10.18	1.90 ± 1.65	5.71 ± 2.86
	50 μL/L	6.67 ± 6.67	24.44 ± 7.70	0.95 ± 1.65	5.71 ± 2.86
	100 μL/L	2.22 ± 3.85	2.22 ± 3.85	0.95 ± 1.65	0.95 ± 1.65
	200 μL/L	0	0	0	0
Spearmint essential oil	20 μL/L	8.89 ± 10.18	15.56 ± 3.85	2.86 ± 2.86	5.71 ± 2.86
	50 μL/L	6.67 ± 6.67	20.00 ± 6.67	1.90 ± 1.65	8.57 ± 2.86
	100 μL/L	3.33 ± 3.33	4.44 ± 7.70	0.95 ± 1.65	1.90 ± 3.30
	200 μL/L	0	0	0	0
Lemon essential oil	20 μL/L	2.22 ± 3.85	15.56 ± 3.85	1.90 ± 3.30	10.48 ± 8.25
	50 μL/L	4.44 ± 3.85	8.89 ± 10.18	0.95 ± 1.65	5.71 ± 5.71
	100 μL/L	5.56 ± 1.92	8.89 ± 10.18	0.95 ± 1.65	2.86 ± 2.86
	200 μL/L	0	2.22 ± 3.85	0.95 ± 1.65	1.90 ± 3.30
Clove essential oil	20 μL/L	2.22 ± 3.85	4.44 ± 3.85	2.86 ± 4.95	1.90 ± 1.65
	50 μL/L	8.89 ± 3.85	11.11 ± 10.18	2.86 ± 2.86	6.67 ± 7.19
	100 μL/L	4.44 ± 7.70	4.44 ± 3.85	0	1.90 ± 1.65
	200 μL/L	0	2.22 ± 3.85	0	0.95 ± 1.65
Jasmine essential oil	20 μL/L	1.11 ± 1.92	2.22 ± 3.85	0.95 ± 1.65	0.95 ± 1.65
	50 μL/L	3.33 ± 3.33	4.44 ± 3.85	1.90 ± 1.65	1.90 ± 1.65
	100 μL/L	0	0	0	0
	200 μL/L	0	0	0	0
Cinnamon essential oil	20 μL/L	8.89 ± 3.85	11.11 ± 3.85	3.81 ± 4.36	3.81 ± 1.65
	50 μL/L	6.67 ± 6.67	11.11 ± 7.70	2.86 ± 2.86	2.86 ± 2.86
	100 μL/L	4.44 ± 3.85	13.33 ± 11.55	0.95 ± 1.65	3.81 ± 2.86
	200 μL/L	2.22 ± 3.85	4.44 ± 3.85	0.95 ± 1.65	1.90 ± 1.65
Perilla essential oil	20 μL/L	6.67 ± 6.67	8.89 ± 3.85	1.90 ± 1.65	5.71 ± 5.71
	50 μL/L	3.33 ± 3.85	8.33 ± 3.85	0.95 ± 1.65	5.71 ± 2.86
	100 μL/L	3.33 ± 3.85	3.33 ± 3.85	0.95 ± 1.65	1.90 ± 3.30
	200 μL/L	0	2.22 ± 3.85	0	0.95 ± 1.65
Citral	20 μL/L	5.56 ± 5.09	6.67 ± 6.67	2.86 ± 2.86	5.71 ± 7.56
	50 μL/L	4.44 ± 3.85	8.89 ± 3.85	1.90 ± 1.65	4.76 ± 5.95
	100 μL/L	0	0	0	0
	200 μL/L	0	0	0	0

Table 3 (continued)

ReagentTreatment dose		Sprouting rate (%)		Sprouting index (%)	
		180 days	270 days	180 days	270 days
Control	0	17.80 ±7.70	73.33 ± 13.33	1.90 ± 1.65	23.81 ± 9.45
Geraniol	20 μL/L	3.33 ± 3.33	8.89 ± 3.85	2.86 ± 2.86	3.81 ± 1.65
	50 μL/L	7.78 ± 5.09	2.22 ± 3.85	2.86 ± 2.86	0.95 ± 1.65
	100 μL/L	0	0	0	0
	200 μL/L	0	0	0	0
Nerol	20 μL/L	2.22 ± 3.85	2.22 ± 3.85	1.90 ± 3.30	0.95 ± 1.65
	50 μL/L	0	8.89 ± 3.85	0	3.81 ± 1.65
	100 μL/L	0	0	0	0
	200 μL/L	0	0	0	0
Eugenol	20 μL/L	15.60 ± 10.18	40.00 ± 6.67	8.57 ± 2.86	22.86 ± 14.85
	50 μL/L	8.89 ± 3.85	22.22 ± 3.85	3.81 ± 1.65	7.62 ± 5.95
	100 μL/L	4.44 ± 3.85	6.67 ± 6.67	1.90 ± 1.65	1.90 ± 1.65
	200 μL/L	0	2.22 ± 3.85	0	0.95 ± 1.65
Cinnamaldehyde	20 μL/L	11.11 ± 3.85	13.33 ± 6.67	5.71 ± 2.86	5.71 ± 5.71
	50 μL/L	4.44 ± 3.85	6.67 ± 6.67	1.90 ± 1.65	3.81 ± 4.36
	100 μL/L	2.22 ± 3.85	2.22 ± 3.85	0.95 ± 1.65	0.95 ± 1.65
	200 μL/L	0	2.22 ± 3.85	0	0.95 ± 1.65
S-(+)-carvone	20 μL/L	6.67 ± 6.67	8.89 ± 3.85	4.76 ± 5.95	4.76 ± 5.95
	50 μL/L	7.11 ± 6.01	22.22 ± 13.88	3.81 ± 4.36	11.43 ± 2.86
	100 μL/L	4.44 ± 3.85	13.33 ± 6.67	1.90 ± 1.65	5.71 ± 2.86
	200 μL/L	0	0	0	0
Ionone	20 μL/L	1.11 ± 1.92	2.22 ± 3.85	1.90 ± 1.65	0.95 ± 1.65
	50 μL/L	8.89 ± 3.85	11.11 ± 3.85	3.81 ± 3.30	9.52 ± 1.65
	100 μL/L	0	24.44 ± 3.85	0	4.76 ± 4.36
	200 μL/L	2.22 ± 3.85	13.33 ± 6.67	0.95 ± 1.65	5.71 ± 7.56
DL-menthol	300 mg/kg	2.22 ± 3.85	4.44 ± 3.85	0.95 ± 1.65	0.95 ± 1.65
	750 mg/kg	0	0	0	0
	1500 mg/kg	0	0	0	0
	3000 mg/kg	0	0	0	0
Raspberry ketone	300 mg/kg	2.22 ± 3.85	48.89 ± 7.70	1.90 ± 3.30	28.57 ± 16.16
	750 mg/kg	4.44 ± 3.85	55.56 ± 10.18	3.81 ± 1.65	50.48 ± 10.03
	1500 mg/kg	6.67 ± 6.67	40.00 ± 6.67	2.86 ± 2.86	64.76 ± 39.42
	3000 mg/kg	13.30 ± 6.67	42.22 ± 6.18	4.76 ± 1.65	31.43 ± 24.91
Chlorine dioxide	10 mg/kg	27.60 ± 17.64	44.44 ± 7.70	9.52 ± 7.19	30.48 ± 28.76
	20 mg/kg	20.00 ± 17.64	33.33 ± 6.67	5.71 ± 4.95	20.95 ± 18.37
	40 mg/kg	15.60 ± 3.85	20.00 ± 6.67	8.57 ± 5.71	5.71 ± 4.95
	80 mg/kg	4.44 ± 3.85	8.89 ± 3.85	2.86 ± 2.86	1.90 ± 1.65
Exogenous ethylene	93.7 μL/L	0	4.44 ± 3.85	0	1.90 ± 1.65
	199.3 μL/L	0	0	0	0
2.5% CIPC	800 mg/kg	0	2.22 ± 3.85	0	0.95 ± 1.65

8.89% and 1.90%, respectively. This result was consistent with previous reports that chlorine dioxide had an inhibitory effect on potato sprouting. The sprouting rate and sprouting index of potato treated with 93.7 μL/L exogenous ethylene were 4.44% and 1.90%, respectively. The results suggested that amongst the three positive treatments, CIPC had the best inhibition effect. It was worth noting that 1500 mg/kg raspberry ketone could promote potato sprouting, and the sprouting index was 64.76%, which was significantly higher than that of control (17.14%) ($P < 0.05$). Besides, the sprout length of raspberry ketone reached 5 cm at 270 days, whilst the control was 1.7 cm.

Amongst all the tested compounds, citronella essential oil and wintergreen essential oil had better inhibition effect than CIPC on potato tuber sprouting. Wintergreen essential oil is mainly composed of methyl salicylate (up to 99%) and contains minor organic ingredients such as α-pinene, myrcene, 3,7-guaiadiene, delta-3-carene, limonene, and delta-cadinene (Eldurini et al. 2021). Wintergreen essential oil is widely used in foods, pesticide, drugs, and cosmetics (Luo et al. 2021), whilst its inhibition effect on potato sprouting has not been reported. Jia et al. found that treatment with citronella essential oil could inhibit potato tuber sprouting and decrease the α-solanine in the skin and flesh of potato tubers (Jia et al. 2019). However, few studies have evaluated the quality changes of potato tubers treated with essential oils, and the effects of wintergreen essential oil and citronella essential oil treatments on potato quality have not been reported. Therefore, after verifying the sprout inhibition effect of citronella essential oil and wintergreen essential oil, quality indexes such as starch content and reducing sugar content were further evaluated.

Sprouting Morphology of Potato Tubers with Essential Oil Treatments

The sprouting morphology of potato tubers treated with citronella essential oil and wintergreen essential oil during storage is shown in Fig. 1. With the increase of the concentration of citronella essential oil and wintergreen essential oil, the number of sprouts on potato tubers decreased; with the treatment concentrations of 100 μL/L and 200 μL/L, none of the potato tubers sprouted. However, the surface of potato tubers were wrinkled with water loss when the concentrations of citronella essential oil and wintergreen essential oil were 200 μL/L. It was observed that the sprout eyes of potato tubers fumigated with essential oil were black. Teper-Bamnolker et al. (2010) also observed this phenomenon. According to the anatomical analysis of sprouts by Gómez-Castillo et al. (2013), eugenol and menthol damaged the potato apical meristem, resulting in epidermal damage and sprout necrosis.

Determination of Reducing Sugar Content

Reducing sugar content is closely related to physiological metabolism of potato and increases during potato germination (Fang et al. 2022). Potatoes stored at low temperatures accumulate high concentrations of reducing sugars and develop a sweet taste; the reducing sugars and nitrogen-containing compounds undergo the “Maillard reaction” at high frying temperatures, making potatoes dark in colour and bitter in taste (Raigond et al. 2018). As shown in Fig. 2, the reducing sugar content of untreated potatoes was low (0.14%). With the extension of storage time, the reducing sugar content of potato tubers in all treatments increased. The reducing sugar content of potato tuber in control

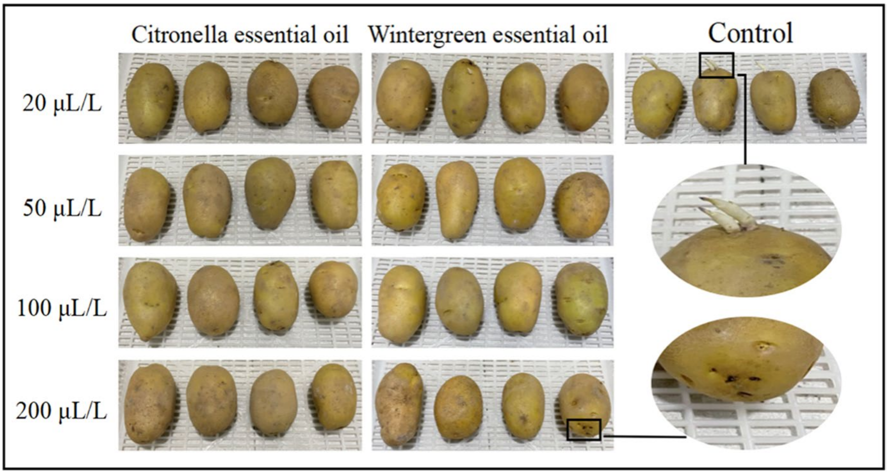

Fig. 1 Effects of citronella and wintergreen essential oil treatments on potato tuber sprouting stored for 270 days at 3 ± 0.5 °C

was significantly higher than that in other treatments when stored at low temperature for 180 days ($P < 0.05$), whilst no significant difference was observed between citronella essential oil and wintergreen essential oil treatments. After 270 days of storage, the reducing sugar content of fresh potatoes (0.14%) was significantly different from that of the untreated potatoes (1.47%), the citronella essential oil-treated potatoes (1.28%), and the wintergreen essential oil-treated potatoes (1.24%) ($P < 0.05$), which was similar to the research results of Shukla et al. (2019). The results showed that the treatments of citronella essential oil and wintergreen essential oil could reduce the accumulation of reducing sugar and keep better quality and colour of potato during processing.

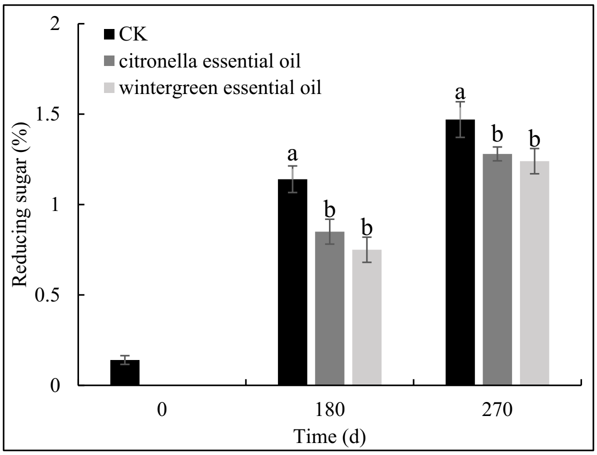

Fig. 2 Effects of citronella and wintergreen essential oil treatments of reducing sugar content in potato tubers after 180- and 270-day storage

Determination of Starch Content

Starch is the main nutrient and energy source of potato tuber, which is closely related to potato storage quality. Starch is continuously converted into reducing sugars under the influence of vacuolar invertase and UDP-glucose pyrophosphorylase (Tai et al. 2020). During storage, the starch content in potato tubers of treated and untreated groups showed a similar trend, which decreased gradually with the extension of storage time (Fig. 3). After 270 days of storage, the starch content of potato tubers treated with citronella essential oil and wintergreen essential oil was 15.32% and 15.80%, respectively, whilst that of the control group was 14.14%. It was observed that the starch content in potatoes treated with citronella essential oil and wintergreen essential oil was less decomposed. Due to the degradation of starch into soluble sugar during storage, the decrease of starch content in control was significantly greater than that in citronella essential oil and wintergreen essential oil treatments (Nourian et al. 2003).

Conclusion

In this study, the inhibitory effects of 18 kinds of plant essential oils on potato sprouting were systematically evaluated. Results showed that 100 μL/L citronella essential oil and wintergreen essential oil could completely inhibit the potato sprouting during storage and had better inhibition effect on sprouting than that of CIPC. In addition, citronella essential oil and wintergreen essential oil treatments slowed down the decrease of starch content, inhibiting the accumulation of reducing sugar, which indicates that these two plant essential oils could be considered as eco-friendly sprout suppressant. This study recommends that optimization

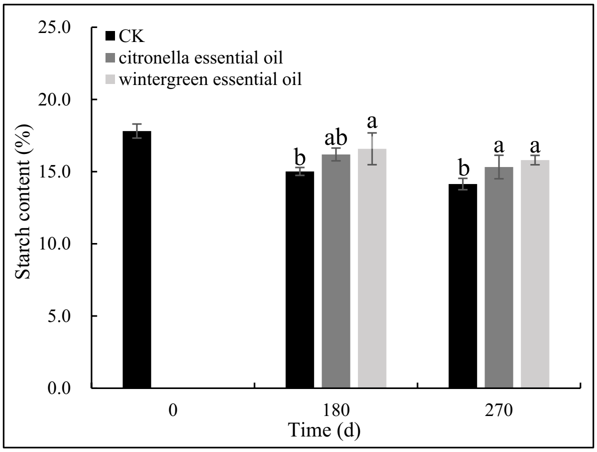

Fig. 3 Effects of citronella and wintergreen essential oil treatments of starch content in potato tubers after 180- and 270-day storage

of essential oil application concentration and application methods should be explored to effectively reduce potato losses caused by sprouting.

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Declarations

Competing Interests The authors declare no competing interests.

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