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REVIEW

Sprout suppression on potato: need to look beyond CIPC for more effective and safer alternatives

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Abstract World over, potatoes are being stored at 8–12 °C (85–90 % RH). This is the most common way of long-term (up to 6 to 9 months) storage of potatoes. The benefit of storing the potatoes within the temperature range of 8–12 °C is minimum accumulation of sugars in stored potato tubers. In sub-temperate, sub-tropical and tropical countries of the world, short-term (3 to 4 months) storage of potatoes is being done by non-refrigerated traditional/on-farm methods. These short- and long-term storage methods keep the stored potatoes suitable not only for table purpose but also for processing. However, once the natural dormancy period of potato is over, the prevailing temperatures in these storage methods favour sprouting and sprout growth. Therefore, use of some sprout suppressant to check the sprout growth becomes essential under these methods of potato storage. CIPC [Isopropyl *N*-(3-chlorophenyl) carbamate] is the most wide spread and commonly used sprout suppressant on potatoes. CIPC has been in use for more than 50 years and research carried out over such a long period use of CIPC has not only enhanced our understanding of its properties and chemistry but also about the production and toxicological status of its metabolites/degradation products. Today, various safety issues and concerns have surfaced primarily due to continuous and long-term use of CIPC. This review presents an appraisal on CIPC and explains the reasons for the long-time dependence on this chemical as a potato sprout suppressant. Issues like maximum residue limit and acceptable daily intake limit are being discussed for CIPC. This article brings an update on practical aspects of potato storage, residue levels of CIPC, efficacy of CIPC as sprout suppressant and health and environmental safety issues linked with CIPC and its metabolites. The aim of this article is to find possible solutions, way outs and future plans that can make the sprout suppression of potatoes safer and more risk free.

Keywords ADIL · CIPC · Metabolite toxicity · MRL · Potato · Potato storage · Residue · Safety issues · Sprout suppressant

Introduction

Potato (*Solanum tuberosum* L.) is an important food crop and it is being grown in nearly 150 countries. Global potato production in the year 2012 was 364.81 million tonnes wherein, the developing countries contributed for 213.74 million tonnes (FAOSTAT 2013a). World potato production has increased at an annual average rate of 4.5 % over the last 10 years. In terms of production, potato has exceeded the growth of many other major food commodities in developing countries and particularly in Asia (IPY 2008; FAO 2008). Today potato is the 4th major food crop after rice, wheat and maize. Just after the harvest, there is huge arrival of potatoes in

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the market resulting in their surplus availability. In the years of higher production, there is glut in developing and economically poor countries. This is primarily due to inadequate facilities and poor infrastructure for storage, marketing and utilization of potatoes in processing. This situation usually cause distress sale by the farmers (Mehta and Ezekiel 2006; Sundaram 2011; Gautam et al. 2013). Fresh potatoes are available only for 2 to 4 months (depending on the geographical region and country). Storage of potatoes is therefore necessary to meet the requirements for the remaining period of a year. Storage of potatoes either for short-term (2 to 4 months, under non-refrigerated conditions) or long-term (5 to 9 months, under refrigerated conditions) helps in reducing the postharvest losses and gluts like situation (Ezekiel et al. 2005; Paul and Ezekiel 2013). The situations and problems pertaining to the storage of potatoes in sub-temperate, sub-tropical and tropical countries of the world are different from that of temperate countries. This is because of the fact that the harvest of potatoes in the former is followed by hot summer months whereas, in the latter harvest is followed by cool winter months.

During storage at temperatures of 8–12 °C, potatoes are treated with a sprout suppressant either once (if stored up to 5 months) or twice (if stored for 6 to 9 months). World over, isopropyl *N*-(3-chlorophenyl) carbamate (CIPC also referred as chlorpropham) is the most commonly used sprout suppressant on potatoes when stored at 8–12 °C (Smith and Bucher 2012). CIPC is primarily an herbicide which was introduced in the year 1951 (Marth and Schultz 1952). After that, its use has gradually spread in developed and then in developing countries (Sawyer and Malagamba 1987; Burton et al. 1992; Tayler et al. 1996; Ezekiel et al. 2005). Many years of research and commercial use has shown the efficacy of CIPC as a sprout suppressant on potatoes especially when they are stored at 8–12 °C. This effect of CIPC is with little or no adverse effect on quality parameters (Rastovski 1987; Tayler et al. 1996; Blenkinsop et al. 2002; Ezekiel et al. 2005; Mehta et al. 2010). Now, it is more than 50 years since the commercial use of CIPC (as sprout suppressant) started on stored potatoes (Teper-Bamnolker et al. 2010; Verhagen et al. 2011). A large number of studies carried out during this period have enhanced our understanding about CIPC, its mode of action, its metabolism in plants and animal and its fate in our environment. This article aims to update and highlight the safety and environmental issues which have surfaced due to continuous and long-term use of CIPC as potato sprout suppressant. Concerns associated with high degree of toxicity as exhibited by metabolites of CIPC (present or formed in the CIPC-treated tubers and also produced in humans on the consumption of CIPC-treated tubers) are also highlighted in this article. Based on the survey of literature and outcome of various studies this article suggests some of the possible solutions, way out and future strategies that will help in making the potato storage and use of sprout suppressant on potatoes safer and more risk free.

Different options of storing the harvested potatoes

Storage at 2–4 °C

Storage of potatoes at 2–4 °C (90–95 % RH) in cold stores is ideal for storing the seed potatoes because at this temperature there is no sprouting or sprout growth. Under this condition, potatoes remain viable for a long period and therefore these tubers can be used as seed potatoes for planting in the subsequent season. This low temperature is however not suitable for storing the potatoes meant for either table or processing purposes. Potatoes stored at this temperature start accumulating reducing sugars (glucose and fructose) and become sweet in taste (Rees et al. 1981; Sonnewald 2001). Consumers do not like to the eat potatoes that taste sweet. Storage of potatoes at 2–4 °C induces a process referred as cold-induced sweetening (CIS). CIS involves degradation of starch (main reserve material present in the potatoes) into reducing sugars (Sonnewald 2001). As a result, potatoes stored at 2–4 °C accumulate reducing sugars in them. Accumulated or higher levels of reducing sugars are also responsible for unacceptable dark brown colour on processed products (chips, crisps, French fries and flakes etc.). This browning is mainly because of a non-enzymatic reaction referred as Maillard reaction (Maillard 1912; Kyriacou et al. 2009; Everts 2012). In this way, potatoes stored at low temperature no longer remain suitable for processing (Ezekiel et al. 2003; Kyriacou et al. 2009).

Short-term storage of potatoes

For short-term storage of potatoes (up to 2–4 months), on-farm methods are practiced by the farmers in most of the potato grown countries (Mehta and Ezekiel 2010; Gautam et al. 2013). These on-farm methods are highly cost-effective and help the farmers in extending the marketing period and thereby fetching more economic benefits (Ezekiel et al. 1999; Paul and Ezekiel 2003a; Kumar and Ezekiel 2006; Mehta and Ezekiel 2010; Paul and Ezekiel 2013). Potatoes are stored in the form of heaps of potatoes or they are placed in pits of appropriate size. Storage of harvested potatoes by above methods are done either in the vicinity of the field (where the potato crop was grown) or the farmers may prefer to store the potatoes near to their house for proper monitoring and look after. Protection from the sun light and possible rains is done by covering the heap of potatoes with straw material and pits by erecting a thatched roof like structure at low height (made from locally available materials) (Paul et al.

2002a, b; Paul and Ezekiel 2004). Besides the above methods, storage of potato in a dark room as such or with provision of evaporative passive cooling, spreading tubers on floor, storing in bins, hanging potatoes in bamboo baskets are also being practiced for short-term storage (Mehta and Ezekiel 2010; Gautam et al. 2013). All the above methods fall in the category of non-refrigerated methods of storing potatoes.

Studies conducted at various centers located in India (representing sub-tropical region) indicated that the temperature inside heap and pit can be 10 to 15 °C lower than the prevailing ambient temperatures. During the storage period of 3 months, temperature and RH varies from 21 to 32 °C and 51 to 95 %, respectively (Kumar et al. 2005; Paul and Ezekiel 2005; Ezekiel et al. 2005). Weight losses due to sprouting and decay of tubers under these on-farm storage methods have been estimated from 10 to 40 % depending upon the duration, type and location of storage, variety, maturity of stored tubers, extent of protection provided to potatoes against sun light, heat of the sun and rains (Paul and Ezekiel 2003a, b; Mehta and Ezekiel 2010). As relatively higher temperature prevails during the period of storage in sub-tropical and tropical regions, these on-farm storage for 2 to 4 months helps in maintaining low levels of reducing sugars in stored tubers (Kumar et al. 2005; Gautam et al. 2013). Because of this, the tubers retain their suitability for table as well as processing purposes. Once the dormancy period (6 to 8 weeks) of harvested and stored potatoes is over, the temperature that prevails under these storage methods (in sub-tropical and tropical regions) favours sprouting necessitating the use of a sprout suppressant to check sprouting and sprout growth.

Long-term storage of potatoes

For long-term storage of potatoes (up to 9 months), storage at 8–12 °C with 85–90 % RH is the most appropriate method and this is normally followed in developed nations. This method of potato storage has become popular in developing countries as well. The basic reason behind selecting the temperature range of 8–12 °C is because of the relationship between the rate of respiration of potato tubers with the storage temperature. At the temperature range of 8–12 °C the rate of respiration of potato tuber is minimum (Burton 1989). The most significant benefit of storing the potatoes within the temperature range of 8–12 °C is that this temperature range allows the minimum accumulation of reducing sugars in stored potato tubers (Smith 1987; Ezekiel et al. 2007a, b). This thereby keeps the stored potatoes suitable for consumption (table and processed potato). However, once the natural dormancy period of tuber is over, this storage temperature of 8–12 °C is favourable for sprouting and sprout growth. Therefore, the use of a potato sprout suppressant becomes essential here.

Adverse consequences of sprouting of potatoes during storage

It is already made clear above that control of sprout growth is a key factor either for short-term or long-term storage of potato. Sprout growth contributes significantly towards the weight loss of the potato. As per an estimate by Burton (1955), respiration increases by 50 % if sprouts on tuber reach to 1 % of the tuber weight (i.e., 1 g of sprout per 100 g fresh weight of tuber). It has been revealed that the epidermis of the sprout is about 100 times more permeable to water in comparison to rest of the surface of the tuber (Burton 1955). Because of this, sprout growth equivalent to 1 % increase in the tuber surface area leads to doubling of the moisture loss from the potato tubers. Respiration as well as evaporation increase rapidly with the onset of sprouting and continuous growth of sprouts. Sprouting therefore results in rapid increase in physiological weight loss of stored tubers. Besides causing the weight loss, sprouting is also highly detrimental to the nutritional status and quality aspects of potatoes (van Es and Hartmans 1987a; Mani et al. 2014). Sprouting leads to higher rate of respiration, remobilization of storage compounds in the potato tubers mainly starch and proteins besides causing shrinkage due to loss of water (Sonnewald and Sonnewald 2014). These changes also cause deterioration in processing quality due to loss in mass, decreased turgor, structural change due to growth of sprout tissue and increase in sugar concentrations due to hydrolysis of starch (Burton et al. 1992; Davies 1990; van Es and Hartmans 1987b; Daniels-Lake et al. 2005). Potato quality parameters such as firmness and content of vitamin C are also adversely affected by sprouting (Rezaee et al. 2011). So, to reduce weight loss and other undesirable physiological and biochemical changes that can adversely affect the quality of potatoes, the use of sprout suppressants has become an integral part of potato storage and potato industry.

CIPC as an effective sprout suppressant for potatoes during short-term and long-term storage

CIPC is a selective and systemic herbicide with an ability to translocate acropetally in plant system (Ashton and Crafts 1981). It has only slight solubility in water (89 mg per litre) but it is highly soluble in organic solvents. Half-life of CIPC in soil is about 65 days at 15 °C and 30 days at 29 °C (O'Neil et al. 2006; EXTOXNET 1996). CIPC acts as a mitotic inhibitor by interfering the process of spindle formation during the cell division (Vaughn and Lehnen 1991). It is known to inhibit protein synthesis, RNA synthesis, activity of β-amylase along with suppression of transpiration and respiration and interfere with of oxidative phosphorylation and photosynthesis

(Vaughn and Lehnen 1991). CIPC is considered as the most effective sprout suppressant for potatoes. It can be converted into emulsifiable concentrate, fogging concentrate, granules and dustable powder (van Vliet and Sparenberg 1970; Corsini et al. 1979; Conte et al. 1995). It is usually applied as a post-harvest fogging treatment on stored potatoes.

Sprout suppression ability of CIPC has been found to be more effective at temperature of 15 °C or below. Its efficacy decreases at temperature higher than 15 °C (Mondy et al. 1992a; Kleinkopf et al. 1997; Ezekiel et al. 2005; Sanli et al. 2010). Research carried out in India has shown the sprout suppression ability of CIPC even at higher storage temperatures (ranging from 21 to 32 °C) although not to the same extent as observed at the storage temperature of 8–12 °C (Ezekiel et al. 2005; Mehta et al. 2007, 2010). On an average, temperature of 18–32 °C (52–88 %) and 19–27 °C (69–92 % R.H) prevails under heaps and pit methods of potato storage respectively during 90 days of storage in sub-tropical conditions when the ambient temperatures may vary between 34 and 41 °C or more (Mehta et al. 2007). Effectiveness of CIPC has been demonstrated at temperature even higher than 15 °C under traditional and non-refrigerated methods of potato storage in number of studies (Ezekiel et al. 2002; Singh et al. 2004; Chandel et al. 2008; Kumar and Ezekiel 2006; Mehta et al. 2007, 2010).

Fogging treatment of CIPC is given either once or twice depending upon the duration of storage period. The dose of CIPC is about 18 g (a.i.) tonne^{-1} of potatoes. Normally two applications are done for long-term storage of potatoes, so total CIPC applied is about 36 g (a. i.) tonne^{-1} of potatoes (Lewis et al. 1997; Ezekiel et al. 2005). In UK, the maximum amount of CIPC that can be applied to fresh market potatoes is 36 g per tonne of potatoes whereas, for processing 63.75 g per tonne of potatoes is allowed (Mohammed 2012). In addition to the use of CIPC as a sprout suppressant, it is also used as an herbicide. As per an estimate, CIPC accounts for about 11 % of the total herbicide sale world-wide (Farawela 2009).

Factors affecting the residue of CIPC in treated potatoes and processed products

Application rates of CIPC may vary depending on the storage temperature, length of storage period and method of application (Mondy et al. 1992a; Sakaliene et al. 2009). Retreatment often becomes necessary to extend sprout inhibition during storage (Corsini et al. 1979; Kleinkopf et al. 1997; Mahajan et al. 2008). Often, there is a lack of uniform distribution of applied CIPC and thereby its concentration in the tubers. For instance; after aerosol or direct spray treatment, CIPC concentrations vary significantly depending upon the location i.e., in top, middle and bottom piles of potatoes (Corsini et al. 1979; Kleinkopf et al. 1997). Potatoes stored in piles had uneven distribution of CIPC, presumably because of differential airflow within the piles (Conte et al. 1995). Potato cultivars also differ in concentration of CIPC dose which is required for the effective control of sprout growth besides being influenced by storage conditions and temperatures (Kleinkopf et al. 2003). All the factors and situations as described above play a role in leading to residue levels of CIPC in the treated potatoes during and after the period of storage.

CIPC is usually applied prior to the start of sprouting (Ravanel and Tissut 1984). Ability of CIPC to suppress the sprout growth is more if it is applied prior to sprouting. Application of CIPC to already sprouted potatoes causes the desiccation of sprouts but its ability to suppress the sprout growth is reduced. Multiple applications of CIPC may be necessary if the permitted application rate is relatively low as it is practiced by European nations (NAPPO 2013). Noel et al. (2004) evaluated the distribution of CIPC after applying it in different formulations. Study revealed that the residue levels of CIPC on the potato tuber depends more on the type of formulation applied than to any other single factor. Treatment of CIPC in the form of dust powder lead to the highest CIPC residue deposit on the potato tuber compared with emulsifiable concentrate while hot fogging showed very low residue level of CIPC. Wilson et al. (1981) observed residue levels of CIPC up to 45 mg per kg of potatoes following the aerosol treatment. Whereas, study by Mondy et al. (1992b), showed that potato tubers dipped in a 1 % emulsion of CIPC resulted in residue level up to 400 mg per kg of potatoes in the peel. This was the maximum residue level recorded in the treated tubers. Peel is known to contain maximum levels of CIPC and in this study residue examination was done just after the treatment under storage at 5 °C (losses of CIPC are minimum at this temperature). Study by Conte et al. (1995) showed presence of 10 times more residues in tubers that were treated with CIPC powder than the tubers treated with aerosol. It was reported by Mehta et al. (2010) that the residue concentration was higher immediately after the spray application of CIPC at a rate of 30 mg per kg of potatoes compared to 20 mg per kg of potatoes but at the end of storage period this difference was no longer detectable. They also recorded 10–20 times lower levels of residue in the cortex than in the peel of treated tubers. Brajesh and Ezekiel (2010) found a correlation between the number of CIPC applications and the residue of CIPC in potato tubers. CIPC was also detected in potato crisps (Lewis et al. 1996) potato chips (Nagami 1997) French fries (Lentza-Rizos and Balokas 2001) and extruded potato peels (Camire et al. 1995). There are other reports where CIPC residue was detected and determined not only in cooked and processed potato products but also in the oil which was used for frying (Ritchie et al. 1983; Nagayama and Kikugawa 1992; Ezekiel and Singh 2007; Park et al. 2009).

Factors contributing for reduction of CIPC residue in treated potatoes

It was observed that up to 45 % of applied CIPC remain present in the soil adhering to the treated and unwashed tubers (Coxon and Filmer 1985). Corsini et al. (1979) reported that the residue of CIPC in peel samples (tuber taken from a large commercial store after aerosol application) were fairly high (15–85 mg L^{-1}) whereas less than 1 mg L^{-1} was found in peeled tubers. Wilson et al. (1981) showed that washing the tubers under running water reduced CIPC concentration from 45 to 40 mg L^{-1}. By applying a more rigorous washing procedure, 88 % of CIPC was removed (level changed from 1.6 to 0.2 mg per kg of potatoes) from potatoes which were earlier treated with an emulsified solution of CIPC (0.1 %) (Tsumurahasegawa et al. 1992). Washing of potatoes with water that were treated with dustable powder of CIPC and stored for 28 days showed reduction in the residue of CIPC from 3.8 to 2.9 mg per kg. This means that 24 % of the CIPC residue leached into the water (Lentza-Rizos and Balokas 2001). Similar observations were recorded by Park (2004) and Sakaliene et al. (2009). In fact presence of CIPC was detected in water which was used for washing the potatoes treated with CIPC. Conte et al. (1995) and Lewis et al. (1996) suggested that removal of CIPC from the potato by peeling is much more effective than washing. On the other hand, Sakaliene et al. (2009) emphasized on cleaning of the surface of the treated tubers by washing to remove CIPC residues because peeling although removes the majority of the chemical but it also removes nutrients from the potato. It is important to mention here that Sakaliene and co workers also laid emphasis on commercial availability of alternative sprout control methods as well. Studies are available where large differences in the residue of CIPC in the peel, unpeeled and peeled tubers have been seen (Coxon and Filmer 1985; Mondy et al. 1992b; Brajesh and Ezekiel 2010). According to Lentza-Rizos and Balokas (2001), peeling removes approximately 91–98 % of the CIPC from the tubers.

Storage time has a substantial effect on the CIPC residue present in the potato tuber. Residue level of CIPC decreases with the duration of storage (Mondy et al. 1992a; Lentza-Rizos and Balokas 2001; Sakaliene et al. 2009; Brajesh and Ezekiel 2010). Reduction in the residue levels of different agrochemicals is also affected by the handling and processing related steps such as; washing, heating, blanching, cooking and frying besides storage duration and storage temperatures (Keikotlhaile et al. 2010; Bajwa and Sandhu 2014). Boiling the potatoes in water or cooking them by steaming resulted in reduced residue of CIPC in cooked tubers as compared to uncooked tubers due to leaching of CIPC into the cooking water (Mondy et al. 1992b). Processing has also been shown to reduce the residue of CIPC in potatoes (Lentza-Rizos and Balokas 2001; Ezekiel and Singh 2007; Sakaliene et al. 2009; Park et al. 2009; Gonzalez-Rodriguez et al. 2011).

Maximum residue limit (MRL) and acceptable daily intake limit (ADIL) for CIPC

On 1st August, 1996, a federal Re-registration Eligibility Decision (RED) for CIPC was issued to continue its use as sprout inhibitor on harvested potatoes in storage by the Environmental Protection Agency (EPA 1996). This decision allowed for a maximum residue limit (MRL; residue tolerance) of 50 mg kg^{-1} of tuber fresh weight (equivalent to 50 ppm). During the year 2002, the established allowable MRL for CIPC for fresh potatoes was reduced to 30 ppm (EPA 2002a, b). In the year 2007, the MRL for potatoes treated by CIPC was fixed at 10 ppm for human consumption across the Europe by Advisory Committee on Pesticides (ACP) (McGowan et al. 2009). While, MRL of 5 to 10 ppm was envisioned by European Union (EU) member countries (Anonymous 2002; Kleinkopf et al. 2003) and 10 ppm by European Commission (2008) and Health and Safety Executive (HSE 2009). As per the regulatory status in three NAPPO (North American Plant Protection Organization) counties (NAPPO 2013), the MRL of CIPC (applied in any form) is 15 ppm for Canada and 30 ppm for USA. These limits also impose restriction on the repeated use of CIPC. However if we wish to see in practical terms, it becomes essential to use the CIPC at least twice for storing the potatoes up to 6 to 9 months.

Actual residue level of CIPC as detected in stored potato tubers treated with CIPC ranged from 8 to 15 ppm (Lentza-Rizos and Balokas 2001; Singh and Ezekiel 2010). The acceptable daily intake limit (ADIL) with respect to CIPC for human body is reported to be 0.05 mg kg^{-1} (of body weight) day^{-1} (Anonymous 1997; Chlorpropham 2003; EFSA 2012). Residue of CIPC is the most frequently encountered chemical present in potatoes and has been regularly found in WPPR/PRC surveys since 1994. In UK, it is applied as a fog according to strict guidelines and only by suitably qualified individuals. Majority of the residue levels reported in the PRC surveys and by industry in UK were below the proposed levels, but levels on two PRC samples in 2003 reached 12 and 20 mg kg^{-1} respectively (Bradshaw and Ogilvy 2006). There are reports that some samples with exceeding MRL were withdrawn from the exporting market (Noel et al. 2004). There are two possible explanations for this 1) The highest recommended application was exceeded even more than which is necessary to control the sprouting and 2) Uneven distribution of CIPC in the piles of stored potatoes (Noel et al. 2002, 2003). If this could be a situation in UK, then the problem of higher residue levels can be expected to be more common in developing and third world countries where neither strict guidelines are followed nor the treatment is being given each time by suitably qualified individuals. Besides this, the old set up and available infrastructure for most of the potato stores may impose hindrance in uniform distribution of CIPC. There is also a tendency of indiscriminate/overuse of CIPC to save the stored potatoes for better price and sometime for the sake of reputation of cold store owners. As per WPPR/PRC surveys since 1994, CIPC is regular and the most frequently encountered residue in potatoes. Study pertaining to whole diet by the USA Food and Drug Administration (FDA) indicated that CIPC is one of the most abundant pesticides in the diet of adults (Daniels-Lake et al. 2011).

Consumption of potatoes in different countries and its relation with ADIL of CIPC

Keeping in view the MRL of CIPC in the whole potato tuber as 5, 10 15, 30 and 50 ppm and the ADIL as 0.05 mg kg^{-1} day^{-1} (as stated above), the data generated for maximum quantity of potatoes a person can consume on daily basis is presented in Table 1. Data on overall consumption of potato (g head^{-1} day^{-1}) in selected countries and regions of the world are presented in Table 2. Now taking into consideration the data presented in Tables 1 and 2 - following inferences can be drawn.

1. Highest consumption of potatoes (507 g head^{-1} day^{-1}) is in Belarus (Table 1). With this much of potato consumption it appears quite obvious that MRL of CIPC in the potatoes should not go beyond 5 ppm (Table 1). But, even with MRL of CIPC as 5 ppm, consumption of potatoes @ 507 g head^{-1} day^{-1} can be considered safe only for the persons with body weight of 50 kg or more (Table 1). Consumption of potatoes equivalent to the national average of Belarus by a person with a body weight of less than 50 kg will possibly expose him/her to a CIPC levels beyond the permissible limit. Next highest consumption of potato is in Ukraine (383 g head^{-1} day^{-1}). With this consumption on daily basis, MRL of CIPC in the potatoes should not go beyond 10 ppm. But, even with MRL of CIPC as 10 and 5 ppm, consumption of 383 g of potatoes in Ukraine cannot be considered safe for the persons with body weight less than 70 and 30 kg, respectively (Table 1).
2. Like the above cases, nations like Poland, Estonia, Russian Federation, Kazakhstan, Malawi and Belgium consume around 300 g of potato per head on daily basis (Table 2). Here again, with the MRL of CIPC at 10 and 5 ppm, people having a body weight less than 60 and 30 kg, respectively are at the risk of taking in the CIPC beyond its permission limit (Table 1). In a similar way, for countries such as; Canada, Bosania & Herzegovina, Nepal, Azerbaijan and Germany and for special groups of nations like; Europe and European Union (where consumption of potatoes is around 200 g head^{-1} day^{-1}) MRL for CIPC should not go beyond 15 ppm (Table 1). But even with the MRL of CIPC at 15, 10 and 5 ppm, people with body weight less than 60, 40 and 20 kg, respectively are at the risk of consuming higher levels of CIPC.

It is true that the quantity and the form in which the CIPC-treated potatoes are consumed (fresh and/or processed product) govern the extent to which an individual will be exposed to CIPC. From the above examples that include different nations with different food habits and in different geographical locations, it is evident that even with the lower recommended MRL of CIPC i.e., 5 and 10 ppm, people can be at risk of higher intake of CIPC. This can happen at least during certain period of year when the availability of potato is totally met from the stored and CIPC treated potatoes. Considering the MRL of 10 ppm for CIPC in potato tuber, countries with potato consumption of around 500, 300 and 200 g head^{-1} day^{-1} are possibly at risk of taking in higher levels of CIPC if people with body weight of 100, 60 and 40 kg, respectively are consuming the CIPC-treated potatoes equivalent to their national average. Taking into consideration the point number 2 as stated above and the data presented in Table 1, it can also be presumed that people in countries like; Malawi, Belgium, Lithuania, Kyrgyzstan, United Kingdom (UK), Rwanda, Romania, Latvia, Ireland and Peru are at the risk level in between the countries consuming 300 and 200 g of potatoes per head on daily basis.

It is important to mention here that 1) Sweden (even with 160 g of per capita consumption per day) has imposed ban on the use of CIPC (Gomez-Castillo et al. 2013), 2) Mexico (with 37 g of per capita consumption per day), which is one of NAPPO country, has not registered any sprout inhibitor for its use on potato (NAPPO 2013), 3) In Netherlands (with 257 g of per capita consumption per day) and Switzerland (with 114 g of per capita consumption per day), S-carvone is also used as potato sprout suppressant at commercial scale and it is marketed with the trade name "TalentTM" (Gomez-Castillo et al. 2013) and 4) Sakaliene et al. (2009) is of the view that until there has been refinement of risk assessment and risk management of the CIPC residues along with an estimation of possible adverse effects of CIPC on the vulnerable groups such as infants and children, the emphasis should be placed on the use of those cultivars that can be stored successfully up to 6 months and longer without any treatment of CIPC. But, keeping in view the effectiveness, widespread use, well established commercial base and non-availability of any other sprout suppressant that can be considered equivalent to CIPC, the use of CIPC is continue. In fact, there are efforts which insist on retaining the use of CIPC in the supply chain of potatoes (Potato Council 2013) and its re-registration not only on the basis of its efficacy to control the sprouting in stored potatoes but also by telling that the use of CIPC on potatoes will continue to be deemed safe (Kippley 2012). In UK, a group named as PICSG (The Potato Industry CIPC

Table 1 Maximum quantity of potato (in gram) a person can consume on daily basis to reach up to the proposed levels of Acceptable Daily Intake Limit (ADIL) of 0.05 mg kg^{-1} of body weight day^{-1} for different Maximum Residue Limits (MRL)

Body weight of an individual (kg)	MRL (mg kg^{-1} of tuber fresh weight or ppm)				
	5	10	15	30	50
5	50	25	17	8	2
10	100	50	33	17	4
20	200	100	67	25	6
30	300	150	100	33	8
40	400	200	133	42	10
50	500	250	167	50	12
60	600	300	200	58	14
70	700	350	233	66	16
80	800	400	267	75	18
90	900	450	300	83	20
100	1000	500	333	91	22

Data in the table are generated based on the values of MRL and ADIL as documented by EPA (1996); Anonymous (1997); EPA (2002a), (2002b); Anonymous (2002); Chlorpropham (2003); Kleinkopf et al. (2003); HSE (2009); McGowan et al. (2009); EFSA (2012); NAPPO (2013)

Stewardship Group) has started a drive “Be CIPC Compliant” in 2013 (http://www.cipccompliant.co.uk/stewardship/, http://www.cipccompliant.co.uk/, http://www.fwi.co.uk/articles/22/07/2013/140121/potato-industry-launches-cipc-stewardship-plan.htm, http://www.fwi.co.uk/articles/05/09/2013/140592/new-campaign-on-the-correct-use-of-cipc-in-potato-stores.htm). This group consists of potato growers, contractors, industries (including Potato Council), processors, regulatory body, research institute etc. The main objective and plea of this group is to make efficient and best use of CIPC as sprout suppressant for stored potatoes. Today, this objective of the PICSG has in fact become more relevant and essential. This need to be implemented world over and in this article, same is being substantiated below by highlighting safety issues and concerns that are now clearly linked with the continuous and long-time use of CIPC on potatoes.

Some important safety issues and environmental concerns related with CIPC

World over, continuous use of CIPC (as a sprout suppressant on potatoes) for a period of more than 50 years and that too at commercial scale (Marth and Schultz 1952; Gomez-Castillo et al. 2013) has brought in some pertinent issues which are related directly to the safety of human, animal, water and environment. Some of such issues are described below.

- CIPC belongs to group of pesticides known as carbamates. CIPC is applied by thermal fogging and this step causes not only the thermal degradation of CIPC but also the breakdown of CIPC. Carbamates break down to aniline based derivatives which have high toxicity profile (Balaji et al. 2006). One of such breakdown product of CIPC is 3-chloroaniline (3-CA) and being aniline based derivative this is considered more polluting and highly toxic than the parent compound itself (Park 2004; Orejuela and Silva 2005; Balaji et al. 2006; Sihtmaee et al. 2010; Smith and Bucher 2012). As per Mohammed et al. (2014, 2015), 3-CA is aromatic amine and dangerous to human and environment. The potential/possible danger with respect to 3-CA can be realized from the fact that other 2 derivatives of aniline i.e., 2-chloroaniline and 4-chloroaniline are already classified as hazardous substances which are possibly carcinogenic to humans (Sihtmaee et al. 2010; Smith and Bucher 2012). The big concern over 3-CA is because it is structurally similar to 4-CA but at the same time chemical structure of CIPC is such that 3-CA and not the 4-CA is produced as one of the metabolic products (Mohammed 2012). In 2012, the European Commission recommended that both CIPC and 3-CA need to be included in the maximum residue level value (MRL) to assess the consumer exposure to pesticide residues in and on food of plant and animal origin (European Commission 2012). As per Mohammed (2012) as well, there are growing concerns not only regarding the safety profile of CIPC but for its degradation products mainly the 3-CA. It is suggested that the high temperature (300–600 °C) of the fogging machine and the contact of CIPC with the metallic surfaces (aluminum pipe of the fogger) mediate the degradation of CIPC via pyrolysis. This thermal degradation (fragmentation and/or rearrangement) is accompanied with the formation of 3-CA (Heikes 1985; Worobey and Sun 1987; Nagayama and Kikugawa 1992; Camire et al. 1995; Park et al. 2009; Przybylski and Bonnet 2009; Paiga et al. 2009). Repeating the application of CIPC during long storage periods not only lead to

Table 2 Per capita consumption of potatoes and potato products in some countries/regions of the world during the year 2011

Country/region	Consumption of potatoes and potato products (g head^{-1} day^{-1})
Belarus	507
Ukraine	383
Poland	314
Estonia	312
Russian Federation	305
Kazakhstan	296
Malawi	293
Belgium	290
Lithuania	279
UK, Kyrgyzstan,	276
Rwanda	274
Romania	272
Netherlands (Holland)	257
Latvia	254
Ireland	247
Peru	226
Canada	215
Bosnia & Herzegovina, Nepal	206
Azerbaijan	197
Germany	194
Chile	185
Finland	183
Bolivia, Czech Republic	181
Greece	179
Lebanon	178
Algeria	177
Spain	170
Luxembourg	168
Iran, Malta	167
Republic of Moldova	165
Denmark	164
Hungary, Iceland	162
Austria, Sweden	160
Portugal	159
The former Yugoslav Republic of Macedonia	158
USA, Norway	152
France	149
Lesotho, Uzbekistan	148
Slovakia	147
New Zealand	145
India	69
Europe	198
European Union	191
America	89
Oceania, Asia	76
Africa	27
Total World	95

Source: FAOSTAT (2013b)

higher levels of 3-CA but also its higher binding to the potato tuber (Mohammed 2012).

- The dietary risk of herbicide and its metabolites cannot be assessed accurately if the residues remain strongly bound to the potato. Strong binding of 3-CA to potato is already reported (Skidmore et al. 2002; Mohammed 2012). This further raises the seriousness of this toxin and its toxicological implications.
- In addition to the above said thermal degradation, microbial degradation (mediated by bacteria) of applied CIPC also results in the formation of 3-CA during prolonged storage especially in the condition of high moisture (which usually prevails in storage environment recommended and practiced for potatoes) (Wolfe et al. 1978; Kleinkopf et al. 1997; David et al. 1998; Park et al. 2009; Verhagen et al. 2011).
- 3-CA is also present as a minor manufacturing impurity/contamination in CIPC formulation (0.05 % of CIPC by weight) (Worobey and Sun 1987; Park et al. 2009). The basic reason for this is the use of 3-CA as one of the substrate along with isopropyl chloroformate for the commercial production of CIPC.
- Once CIPC enters in human/mammals, animal and plant/potato tubers, it degrades into metabolites such as 3-CA; isopropyl *N*-4 hydroxy-3-chlorophenyl carbamate; isopropyl-*N*-5-chloro-2-hydroxyphenyl carbamate; 3, 3′-dichloro azobenzene; p-methoxy-chlorpropham; 3-chloro-4 hydroxyaniline; 3-chloro-4 methoxyaniline; 1-hydroxy-2 propyl-3-chlorocarbanilate and 3′-chloroacetanilide; isopropyl N-(3-chloro-4-methoxyphenyl) carbamate; isopropyl N-(3-chloro-4-hydroxyphenyl) carbamate etc. (Davis et al. 1977; Kidd and James 1991; Carrera et al. 1998; Orejuela and Silva 2005; Balaji et al. 2006; Smith and Bucher 2012). These metabolites are reported to be cytolytic, highly toxic, carcinogenic, cause reduction in ATP synthesis, bring about modifications in cell permeability besides being pollutants (Davis et al. 1977; Heikes 1985; Worobey and Sun 1987; Worobey et al. 1987; Kidd and James 1991; Carrera et al. 1998; Balaji et al. 2006; Smith and Bucher 2012). Out of these metabolites of CIPC, 3-CA is one of the metabolites which are also produced in mammals on consumption of CIPC. Approximately 20 % of CIPC taken in by mammalian body may get metabolized into 3-CA.
- CIPC is slightly volatile (NAPPO 2013) and as described above, tuberes can also metabolize it slowly into the compounds which are more toxic than CIPC itself. This volatilization and breakdown of CIPC reduces the efficacy of CIPC in two ways 1) effective CIPC available in the tuber is reduced and 2) the metabolites produced show either little or no sprout suppression ability.
- It was noticed by Nagayama and Kikugawa (1992) that putting the CIPC in soybean oil and heating it at 180 °C give rise to a gradual decrease in CIPC with an accompanying production and increase in the levels of 3-CA. This suggests that frying of CIPC treated potatoes (during processing) results in the degradation of CIPC into 3-CA (Park 2004; Worobey and Sun 1987; Worobey et al. 1987; Park et al. 2009).
- Recent work on the kinetics of degradations of CIPC and also its metabolites (by hydrolysis, biolysis, photolysis and thermal processes) and their partitioning in air, water and soil indicated vast differences in the lab and field conditions (Smith and Bucher 2012). Under lab conditions, there is usually overestimation of degradation. This therefore necessitates for looking into the actual kinetics as a part of decision making process by the regulatory agencies in deciding the MRL and ADIL of CIPC.
- Occasionally, application of CIPC to control sprouting can fail or remains inefficient to control the sprouting. Timing of CIPC application is critical to its success in suppression of sprout growth. Late or untimely application of first or second application of CIPC produces mixed results ranging from adequate sprout inhibition to complete failure (Kleinkopf et al. 2003; Park 2004; Park et al. 2009). This situation may put the demand/pressure for additional application of CIPC and that too at still higher dose. This in turn will enhance the residue level of CIPC in the tubers.
- CIPC blocks the spindle formation and in doing so the process of cell division (mitosis) is inhibited (Ashton and Crafts 1981; Vaughn and Lehnen 1991; Kleinkopf et al. 2003). In this way, absence of cellular division prevents the sprouting. With this mode of action, CIPC in fact targets the very essential and an indispensible cellular process which is very basic and common to both, plants and animals. Besides this, CIPC also causes the alteration in cellular structure and functions.
- CIPC is very less soluble in water (89 mg per litre) and therefore it requires organic solvents (like; methanol or dichloromethane) for its application as a fogging treatment. Heavy use of these solvents not only adds to the toxicity status but also impose the risk on the personnel involved in treating/fogging application and to the immediate environment.
- As already stated above that CIPC has only limited solubility in water but even with this little solubility its residue in the washed water contaminate water bodies and environment (Park 2004). There are growing levels of contamination to the environment, soil and water bodies with the breakdown products/metabolites of CIPC is a matter of more serious concern, especially with respect to 3-CA (Angioi et al. 2005). This is due to low degradation of 3-CA. It is also important to mention here that in comparison to CIPC, solubility of 3-CA is quite high in water (5,400 mg L^{-1}).

- CIPC is among the three pesticides which has been found in the highest concentrations in the diet of the average American and comprises 90 % of the total synthetic chemical residue in US potatoes and in this way also it is going to be a health concern (Gunderson 1988; Prange et al. 1997; Daniels-Lake et al. 2011). Recent literature points out clearly that the CIPC residue left in the tuber is harmful for human body (El-Awady Aml et al. 2014) and new legislation is also limiting the use of CIPC (Cools et al. 2014). The reason for such an impact of CIPC can be understood in a more clear way from the following data. The approved limit of CIPC application per tonne of potatoes (meant for processing, during the season) is 63.75 g (Mohammed 2012). An average sized potato store of 1, 000 tonnes could potentially be treated with 63.750 kg of CIPC (Smith and Bucher 2012). Now assuming the latest MRL (the legal maximum) for CIPC as 10 mg CIPC kg^{-1} of potatoes as set by HSE (2009), about 53.750 kg of the CIPC chemical is unaccounted for in a storage season. This shows that vast amount of CIPC is lost to the store fabric, atmosphere, soil and water (Smith and Bucher 2012). With the above practice in use the buildup levels of CIPC has kept on increasing year after year.
- A few criteria have been laid for a potato sprout suppressant that can be considered as ideal by many workers (Beveridge et al. 1981a; Vaughn and Spencer 1991; Teper-Bamnolker et al. 2010). These criteria include 1) The chemical should effectively inhibit sprouting under commercial storage, 2) The chemical should have minimum effect on the quality parameters of the potatoes (weight loss, sugar content, appearance etc.), 3) There should be low toxicity of the sprout suppressant and its residues do not cause problems to humans, 4) The chemical should break down rapidly and it need to be environmentally friendly. Our updated understanding on CIPC as of today indicate it clearly that first two criteria are being met by CIPC but definitely there are problems, issues and growing concerns with respect to last two criteria.
- Isopropylphenyl carbamate (referred as IPC or propham) is also an herbicide which belongs to the same class as CIPC. Initially, it was also in use commercially to prevent sprouting (mostly in combination with CIPC) but now its application has been banned in most of the countries. IPC is also not supported in the countries of European Union (EU) due to ecological concern (Mohammed 2012).
- With respect to CIPC it is also true that among the herbicides it is very toxic to worms and relatively more harmful to birds, fishes and other aquatic animals, environment and ecosystem (Kidd and James 1991; EXTOXNET 1996; Anonymous 1997; Anonymous 2002; Kleinkopf et al. 2003; Greene and Pohanish 2005; O'Neil et al. 2006; HSE 2009; Safety Data 2009; MSDS 2009; Paul et al. 2014). Both, CIPC and 3-CA are categorized under List I and Hazardous Substances which should be avoided in ground water (EPA 2010). As per European Community Pollutant Circular No 90–55 (1990), 3-CA is recognized as a toxic water pollutant and harmful to aquatic life (David et al. 1998).
- About 60 % of the total potato production is used for human consumption and remaining 40 % is used for other purposes including animal feed, seed tubers, industry and pharmaceutical products (Topcu et al. 2010). Here it becomes important to mention that use of CIPC treated potatoes as feed may also pose health risks and safety concerns for animals as well.

In view of the above listed facts, recent understanding on toxicological aspects, potential risks and growing concerns - CIPC and its metabolites needs to be handled and used in a more judicious way because there is potential impact and implications of the CIPC and its metabolites on humans and environment. Inferences drawn above in point number 1 and 2 (although not based on actual trials and sampling) appear to be relevant and factious in view of the critical details presented above for CIPC and its metabolites.

Increasing the efficacy of CIPC as sprout suppressant and reducing its residue in potatoes

Contamination of store fabric, food chain, water/ground water bodies with CIPC and its metabolites has emerged as a serious concern. Decreasing the degradation of CIPC into its toxic metabolites and increasing the efficacy of CIPC further for its ability to suppress the sprout growth are the two possible options that can be utilized to tackle the problems associated with CIPC. It is suggested that the concentration of CIPC breakdown product, for example 3-CA, can be reduced by modifying the process of fogging. This can be done by lowering the fogging temperature and avoiding the metal pipes (used to carry CIPC fog into the potato store). The formation of 3-CA in the air samples during fogging was found to be abolished at burning temperature of 190 °C. This was in sharp contrast when usual burning temperature of 600 °C was used (Mohammed 2012). This modification however would not reduce the levels of 3-CA which is formed due to the microbial degradation and this aspect therefore need to be resolved. UK Potato Council [Sutton Bridge Experimental Unit (SBEU)] in collaboration with the University of Glasgow and others initiated the studies to improve the efficiency of sprout control by CIPC. Best practice guidelines for the most effective use of CIPC are being made available and these are also updated regularly [www.potato.org.uk and www.assuredproduce.co.uk/Aproduce/]. The guidelines usually include store layout, application methods, dose, timings of CIPC treatments, deposition and decline rates etc. In view of the current situation, enhancing the efficacy of CIPC further should be a priority area of research. Innovative refinements in the instrumentation and delivery system will also contribute significantly in achieving the above objectives.

It is reported that large amounts of field soil if remains adhered around the harvested tubers than it can impair the distribution of the CIPC vapour. This not only reduces the efficacy of CIPC treatment as sprout suppressant but it also leads to non-uniformity in treatment (NAPPO 2013). This aspect needs to be taken care by managing the harvesting and field related practices. It has been seen that second or even third application of CIPC for satisfactory control of sprouts for long-term storage are governed primarily by factors such as cultivar or extent to which potato faced the stresses. In this direction, suitable variety selection, agronomic practices and postharvest management practices in the form of a time schedule can be of immense help in either skipping or minimizing the number of CIPC applications. It has been noticed that a single aerosol application of CIPC @ 20 to 25 g per tonne of tubers provide effective sprout control up to 9 months in variety Russet Burbank when stored at 7.2 °C (NAPPO 2013). This variety specific response need to be investigated so that we can come to know the very basis of this. If this is because of some varietal feature/s of Russet Burbank then efforts can be taken up in the direction of incorporating such feature/s into other varieties as well. Besides providing new physiological and biochemical understanding, such work will significantly contribute in reducing the residues of CIPC in the treated potatoes.

Enhancing the natural dormancy period of potato tubers from its present duration of 2 to 4 month (depending on the temperature that prevails after the harvest and variety) to 4 to 6 months or even more can also be one of the indirect approaches. This is an interesting area of work as this will prove to be highly beneficial in reducing the frequency of CIPC treatment to the stored potatoes. Further, there is a need to look for the possibility of using some carriers with CIPC for enhancing its delivery and uptake by the stored potatoes. Scientific information generated from the studies pertaining to the steps like; washing with water, soaking in solutions of salt and some chemicals (chlorine, chlorine dioxide, hydrogen peroxide, ozone, acetic acid, hydroxy peracetic acid, iprodione and detergents), peeling, trimming, blanching, boiling, frying cooking, steaming and canning etc. can assist in degrading and removing of the applied agrochemical from the edible commodities before their consumption (Sakaliene et al. 2009; Keikotlhaile et al. 2010; Bajwa and Sandhu 2014). These aspect need to be refined and standardized so that the residue levels of CIPC and its breakdown products can be reduced to the maximum possible extent.

CIPC is reported to undergo volatilization and get degraded if expose to UV radiation (Bradshaw and Ogilvy 2006). So, attempts need to be made to look into the possible use of UV radiation mediated degradation of CIPC via titanium dioxide coating (as such or with nano particles, when exposed to UV light). This method and procedure is already in use for breaking down the volatile organic compounds (VOCs) into CO_2. So, such method can be utilized to decontaminate the storage space from the unused and accumulated CIPC and its metabolites when the facility is not in use. This strategy may prove useful in reducing the overall built-up of CIPC and its metabolites due to continuous use of CIPC for number of years. Some of other novel ways of reducing the levels of residue (either CIPC or its metabolites) also need to be developed and tested for CIPC-treated tubers as well. This can then be applied either when the storage period of potatoes is over or just prior to the consumption/utilization of potatoes by processing industry.

The time laps after the CIPC treatment is known to decrease the residue level of CIPC in the tubers. So, one way that can make the use of CIPC more safe is by strictly following the schedule and regulations with respect to the time gap that need to be maintained between the last CIPC treatment and the time when the potatoes are to be sent to the market. For CIPC, such details are known but similar details are by enlarging missing for different toxic products/metabolites that are formed from CIPC and also present in the CIPC-treated potatoes. This aspect therefore needs to be investigated so that appropriate guidelines and recommendations can be made available in future. Another important area is to search for alternatives of CIPC. Considerable work has been done and is in progress. This aspect is therefore, described below in detail.

Alternatives of CIPC and possibility of integrated and effective use in combinations

Over a period of time, researchers have gradually become aware of some of the practical, technical, safety related problems and issues linked with the use of CIPC. Attempts are therefore being made to find out some alternative to CIPC that can be safer, applied more easily and also cost-effective (Sawyer and Thorne 1962; Beveridge et al. 1981a, b; Weerd 2005; Gomez-Castillo et al. 2013; Paul et al. 2014). Sprout suppression by long-chain alcohols was reported by Burton in the year 1956 (Burton 1956). The C_9 alcohols were effective in controlling the growth of sprouts however the alcohols with branched chain were found to be ineffective (Sawyer and Thorne 1962). Later on, Meigh (1969) and Burton (1989) reported that compounds containing 9–10 carbon atoms per molecule were effective in suppressing the sprout growth. Nonanol (3, 5, 5-trimethylhexan-1-ol) suppressed sprout growth but its suppressive effect was not persistent as the sprout growth was noticed again within 2–3 weeks (Burton et al. 1992). Many other chemicals including cineole and fenchone (Vaughn and Spencer 1991), lavender, sage and rosemary essential oil (Vokou et al. 1993), maleic hydrazide

(Mamani Moreno et al. 2012), short-chain alcohols, aldehydes such as salicylaldehyde, benzaldehyde, cinnamaldehyde, aliphatic aldehydes, ketones, derivative of phenoxy acetic acid (Vaughn and Spencer 1993; Paul and Ezekiel 2002), triadimefon (Paul and Ezekiel 2003c), volatile monoterpenes like 1, 8-cineole and eucalyptus oil (Vaughn and Spencer 1991; Knowles and Knowles 2007), essential oils like caraway (Hartmans et al. 1995; Oosterhaven et al. 1995; Sorce et al. 1997; Sanli et al. 2010; Teper-Bamnolker et al. 2010; Rentzsch et al. 2012; Gomez-Castillo et al. 2013), peppermint, spearmint, clove oil, mint oil (Kleinkopf et al. 2003; Rentzsch et al. 2012; Teper-Bamnolker et al. 2010; Gomez-Castillo et al. 2013), mono, di and trimethyl-naphthalenes, benzothiopenes, menthone and neomenthol (Coleman et al. 2001), mentha oil (Mehta and Kaul 2002), essential oils from fresh aerial parts of *Mentha spicata* (Chauhan et al. 2011) and formulation of essential oils from *Chenopodium ambrosioides* and *Lippia multiflora* (Owolabi et al. 2010) were tested and found to suppress the sprouting and sprout growth. Chemicals like; ethylene (Prange et al. 2005, 1997, 1998; Daniels-Lake et al. 2005), ozone (Daniels-Lake et al. 1996), glyphosate (Paul and Ezekiel 2006a, 2006b), hydrogen peroxide (Afek et al. 2000; Kleinkopf et al. 2003; Bajji et al. 2007), 1, 4-dimethyl naphthalene 1, 4-DMN (de Weerd et al. 2010; Campbell et al. 2010; Canada 2011; Potato 2012), 2, 6-diisopropyl naphthalene (2, 6-DIPN) (Lewis et al. 1997) were also tested to control the sprout growth on potatoes. Ethyl ester of 2, 4-dichlorophenoxy acetic acid (2, 4-D), ethyl ester of 2, 4, 5-trichlorophenoxy acetic acid (2, 4, 5-T), imazethapyr and glyphosate are herbicides like CIPC and they are also reported to be effective and better than lower alcohols and acetaldehyde in suppressing the sprout growth on potatoes (Burton 1989; Burton et al. 1992; Tayler et al. 1996; Paul and Ezekiel 2002; Paul and Ezekiel 2006a, b; Paul et al. 2014; Hutchinson et al. 2014). Perhaps in view of either practical problems or due to issues related to human health and environment safety further work with these herbicides as an alternative to CIPC was not taken up. In addition to above described sprout suppressants, suppression of sprout growth has also been demonstrated by the use of γ radiations (Ezekiel et al. 2008; Olsen et al. 2011; Rezaee et al. 2011; Lu et al. 2012a, b) and UV-C light (Cools et al. 2014).

Studies on the possibilities of replacing the CIPC with naturally occurring compounds showed that in spite of great deal of work on various options so far none of the option has assumed wide spread use, commercial angle and acceptability. Till today, we do not have either equivalent or better alternative than CIPC (Mohammed 2012). It is true that most of the available alternatives of CIPC provide only short-term and reversible sprout suppression and therefore they are not good candidates for long-term storage of potatoes. Lesser efficacy, frequent/multiple applications and higher cost in comparison to CIPC are the main demerits for most of the other sprout suppressants. For long-term storage, most of the alternatives need to be applied number of times and this will result in cost escalation beyond a feasible limit. David Walker, Chairman of FPSA (The Fresh Potatoes Suppliers Association), stated that alternatives of CIPC play a more significant role in sprout suppression on fresh potatoes but, CIPC is critical and there is no complete alternative solution (Potato 2013). Likewise, Director-General Richard Harris of PPA (The Potato Processor's Association) said that for the long-term storage of processing potatoes the potato industry is totally dependent upon CIPC. According to him the sector would witness devastation if potatoes are not supplied for 52 weeks of the year (Potato 2013). From the point of potato industry and the people who are directly or indirectly associated with it, utility as well as dependency on CIPC can be understood. But at the same time, it should also need to be realized that continuous and long-time dependence on only one type of sprout suppressant is not wise and that too when issues related to toxicity, acceptable residue levels and safety aspects have been raised and becoming more clear.

Use of an integrated approach to control the sprout for long-term is suggested by making use of CIPC in conjunction with other sprout suppressants by Bradshaw and Ogilvy (2006). This can help in reducing the residue levels of CIPC. An alternative to CIPC that does not interfere with wound-healing can be applied early and may prove more effective for varieties that exhibit short dormancy duration. Introduction of alternative/s will definitely help in reducing the present dose and/or frequency of CIPC treatments and this in turn will reduce the residue levels of CIPC in the tubers. In this way, CIPC and alternative sprout suppressants can offer a viable, cost-effective, safer and environmentally friendly approach. This will reduce not only the residue levels of CIPC but also the levels of its degradation products/metabolites which pose more risk to health and environment. In USA, sprouting is also managed with application of 1, 4 DMN consecutively with CIPC. The CIPC is applied first (16–22 g per tonne of potatoes one time as a single application) and then the 1, 4-DMN is applied. In comparison with the CIPC treatment alone; 1, 4-DMN is found to be effective in achieving adequate suppression of sprouts on potatoes if potatoes are previously treated with CIPC (Kleinkopf et al. 2003; Campbell et al. 2010). Now for long-term control of sprouting, in addition to the preharvest treatment of potato crop with maleic hydrazide, CIPC can be applied to the harvested potatoes during the storage (NAPPO 2013). The possibility and prospects of using pre-harvest foliar application of glyphosate as an additional or alternative/supplementary to CIPC as sprout suppressant are explored by Paul et al. (2014). S-carvone is another sprout suppressant. It is a natural volatile that leaves little or no residue. It is costly and therefore usually it is used in organic potato stores (Teper-Bamnolker et al. 2010; Rentzsch et al. 2012). Output and outcome of recent research towards the refinement of instrumentation and application methodologies with worked out sequence of treatments with different sprout inhibitors (one after another) will help in reducing the application rates of CIPC.

3-Decen-2-one (an unsaturated ketone) has been found to exhibit sprout suppression ability. Presently, it is permitted in the USA as a flavouring agent in foods. Registration of this compound as a potato sprout inhibitor is underway in both Canada and the USA. This compound causes physical damage to the sprouts and provides season-long control with only a few applications. Aerosol applications will give approximately 3 to 8 weeks of sprout control depending upon variety and storage temperature. Inhibitory effect of 3-decen-2-one is not permanent and therefore the tubers will eventually re-sprout. Several other compounds like salicylaldehydes, jasmonates and farnesene have also been added to the list of compounds that can inhibit the sprouting of potato. They are effective but none of them have a lasting effect. Therefore, search for effective and viable alternatives of CIPC need to be looked and probed with new angles and ideas.

Recently, a new type of potato sprout inhibitor was discovered at Washington State University by Rick Knowles and Lisa Knowles. This patented inhibitor is also approved for commercial use in US (Knowles 2013). This chemical has been registration for its use in Canada and Europe. The inhibitor is reported to be a naturally occurring molecule and it is classified as biopesticide by EPA. As per report, the inhibitor offers safe, comprehensive long-term storage control and requires no capital investment by the consumers as it can be easily applied using existing equipment. For commercial use, the trade name given to this inhibitor is SmartBlock® and rights for its marketing is owned by AMVAC (American Vanguard Corporation). Investigations have revealed that one application of this chemical inhibits sprouting for 2 to 3 months. Two to three applications provide effective sprout suppression for full season (8 to 9 months) and that too with little residue.

Conclusions and way forward

Suitability of potatoes for long-time storage makes them one of the most important foods worldwide and in one way comparable to that of grains. It has been suggested that potatoes can be an alternative for costly cereal crops because potatoes are traded globally while cereals are not (IPY 2008; FAO 2008; Lutaladio and Castaidi 2009). Prolonged storability of potatoes and availability of different storage options enables the potato processing industry to operate round the year. With these advantages and ability of potato to get adaptive to a wide range of climatic conditions and soil types (Burlingame et al. 2009; Ghazavi and Houshmand 2010; Topcu et al. 2010), it is now realized that potato is world's single most important tuber crop with a vital role in the global food system. With these benefits it is quite obvious that in future potato is going to play a major role in contributing to food and nutrition security, poverty alleviation, environmental conservation and sustainable development.

One of the most important requirements of harvested potatoes is timely and proper storage. It is in this context that aspects associated with potato storage are very crucial. Today world over the most prevalent long-term (6 to 9 months) storage method for potatoes is at temperature of 8–12 °C (85–90 % RH) along with the use of CIPC as sprout suppressant. The time line of information generated on potato for a period of over 60 years is described and discussed in this article by covering various aspects including; postharvest management, storage problems, accumulation of reducing sugars, CIS, darkening of fried products, storage methods, CIPC as sprout suppressant, merits and demerits of CIPC and its continuous use on potatoes during storage, search for alternatives of CIPC, enhancement in our understanding on the toxicological profile of CIPC especially its metabolites/degradation products (produced at the time of its fogging due to high temperature of fogger), uptake of these products by the stored potatoes, formation of CIPC degradation products in potatoes (during storage) and in human/mammals (on the consumption of CIPC treated potatoes). The information revealed very clearly that the use of CIPC has provided the required boost and support to the potato production and potato based processing industries but at the same time it has also gradually made us over-dependent on its use as a potato sprout suppressant.

Keeping in view the versatility of potato as a crop and its diverse uses there will be further increase in the consumption of potatoes and potato products in many countries including the developed and developing countries (IPY 2008; FAO 2008). The information available till date and the data presented here on the MRL and ADIL of CIPC do point out the problems linked with the residue of CIPC and its harmful metabolites. Studies have already reported that toxicological evaluation of CIPC as tested and documented under lab conditions is an underestimation. At present, there is wide variation in the quantity of potatoes that is consumed by the people living in different countries. This thereby suggests that parameters like MRL and ADIL need to be country specific (in view of their food habits and food consumption patterns). In this context, it is important that different regulatory agencies should take initiative and relook into the criteria on which parameters like; MRL and ADIL are fixed, advocated and recommended. Fixing of these limits need to be evaluated by taking into consideration not only the CIPC but also the metabolite/s produced by CIPC. This aspect is in fact already highlighted by Gonzalez-Rodriguez et al. (2011); Smith and Bucher (2012); and European Commission (2012). Such inclusions should not remain restricted only to one particular harmful degradation product/metabolite but to all such toxic breakdown products/metabolites which are and can be formed or present in response to the treatment of a given sprout suppressant. Breakdown products/metabolites can be formed as a result of metabolism in the treated commodity itself or later in the humans on the consumption of treated commodity. Such an approach will also be needed for other agrochemical/pesticides as well.

In future, a viable, effective and low-cost alternative to CIPC for potato sprout suppression will definitely be needed. But till then, importance needs to be given to the concept of using at least two different types of sprout suppressants (use of CIPC with another sprout suppressant, one after another in a required sequence). This aspect needs to be disseminated widely by developing suitable combination/s depending up on the need, situation, feasibility, location, cost, acceptance and preference etc. Time has come when more serious R & D is required for enhancing the effectiveness and efficacy of CIPC. Guidelines for most effective use of CIPC as introduced and also updated regularly by UK need to be introduced in other countries as well. This is important as this will help in curbing the indiscriminate use of CIPC (in terms of use of higher doses and more than the required number of applications). These changes will help in reducing the overall dose of CIPC and its residue in tubers.

The final practical output of various investigations that aimed to understand the CIS and making the potato resistant to CIS is still awaited in terms of actual practicalities and large-scale applicability across the countries. If this can be achieved, then the potatoes can be stored up to 8 to 9 months at low temperature (2–4 °C) and that too without any use of sprout suppressant. But again, this option is more energy/power dependent besides being costly. These aspects will make it less available, assessable and acceptable in developing and third world countries of the world. Therefore, it is necessary to store the potatoes with judicious and effective use of sprout suppressant taking into consideration health and environment issues.

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