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Review

Extracts of tomatoes and potatoes as biopesticides: a review

Joshua Ibukun Adebomi[1] · Jianfeng Guo[1,2] · Catherine Hui Niu[1]

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Abstract
Pest control is crucial to protect animals and plants in the agriculture industry. Biopesticides, because of being environmentally friendly and renewable, have attracted more attention in recent years. Nonetheless, due to costs, issues with controlling pests across various agricultural methods, and supplementary obstacles, biopesticides constitute a minor portion of the worldwide market for crop protection. Agricultural products like tomatoes and potatoes stand as examples of Solanaceae, a significant plant family with numerous economically vital species. From 2022 to 2027, the tomato market is anticipated to have a Compound Annual Growth Rate (CAGR) of 5.6%. Likewise, the worldwide market size for potato starch is predicted to attain a value of $4.9 billion with a market growth of 3.5% CAGR by 2027. After harvest, tomato and potato by-products such as leaves, peels, stems, and so on are generated as by-products, but they have not been effectively utilized. Recent research studies show that extract of the byproducts contains components such as glycoalkaloids, flavonoids, additional phenolics, ketones, and so on, which can be used as biopesticides. For proper pest control and utilization of the by-products in agriculture and related industries, this paper provides a review of recent progress on the research of the active components in the extracts of agricultural by-products of tomato and potato, their roles for pest control, extraction methods, challenges, its future development, and more.

Keywords Biopesticides · Solanaceae · Tomato · Potato · Pest control · Natural plants

1 Introduction

The global population relies significantly on agricultural goods, sourced from both plants and animals for consumption. These products are encountering challenges because of agricultural pests. For many decades, synthetic pesticides have been used to control pests, which have played roles in improving the yield and quality of agricultural products worldwide [1]. Today, it is one of the most used methods in controlling pests. However, extensive uses of synthetic pesticides have resulted in adverse health effects for humans, other forms of life, and their ecosystem. The continuous use of pesticides in the environment usually leads to accumulation and with time, this process makes organisms to be resistant to their usage. Furthermore, they undergo bioaccumulation and decompose slowly. Contact with pesticides has been associated with the development of cancer and neuronal damage in humans [2]. These negative effects led to an incentive to develop alternative solutions for pest control that are environmentally friendly and aim to satisfy the increasing need for food safety and quality.

✉ Catherine Hui Niu, catherine.niu@usask.ca | [1]Department of Chemical and Biological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada. [2]School of Chemical Engineering and Technology, North University of China, Taiyuan 030051, Shanxi, China.

Several botanical and microbial substances display notable biological effects linked to the existence of secondary metabolites. Progressed biotechnology and novel molecular techniques have furnished means to comprehend the control and enhance the synthesis of desired secondary metabolites. Furthermore, evidence has shown that naturally existing chemicals for safeguarding crops present innovative strategies for controlling pests. These strategies involve introducing fresh reservoirs of biologically potent natural compounds that possess qualities such as biodegradability, low risk to mammals, and eco-friendly properties [3].

This type of pesticide is known as biopesticide. Their route of functionalities is through predatory, parasitic, or chemical relationships which have been used in controlling and killing several types of pests. For example, they might repel pests, disrupt their mating, or stunt their growth without killing them [4]. In recent years, biopesticides have gained significant interest as potential substitutes for synthetic pesticides in pest management to enhance food safety and quality, reduce soil contamination by chemicals, and protect the environment. Their sources include plants, animals, bacteria, and some minerals. Importantly, they carry a low level of risk to both human health and the environment [5].

Among the diversified sources, plants such as Solanaceae and their byproducts such as leaves, peels, stems, and tubers are proliferated with alkaloids, flavonoids, and phenolic compounds which have pesticidal properties and thus, promising for producing biopesticides. In the plant kingdom, there is a substantial generation of biologically active compounds, and the products derived from it are used by humans in several ways such as medicinal uses (e.g., deadly nightshade, jimson weed), sustenance production (e.g., tomatoes and potatoes), pharmaceuticals (e.g., tobacco), and so on. To protect crops, Solanaceae plants have the prospect of giving birth to new chemicals which are often called pest control agents and they can control fungi, mites, and insects. The compounds comprise various substances, that consist of nitrogen (e.g., alkaloids and glucosinolates), phenols (such as phenolic acids, coumarins, flavonoids, tannins, and lignin), carbon and hydrogen (e.g., terpenes existing in plant volatiles, cardiac glycosides, carotenoids, and sterols), and ketones [6]. The metabolites such as alkaloids can effectively kill pests such as *Sclerotinia sclerotiorum* which causes diseases of canola, sunflower, flax, pulses, and so on. Particularly, the above-mentioned metabolites exist in the organs of Solanaceae such as leaves, peels, and stems of tomatoes, potatoes, etc. They form significant cost-effective sources as feedstock to produce biopesticides [7].

However, biopesticides constitute a minor proportion of the overall global crop protection market because of the costs and impacts on pest issues within varied agricultural systems. Production needs to be enhanced. There is much space to reduce the costs of extraction and separation of the extracts of the plant materials. In addition, some biopesticides are volatile. The release of biopesticides upon application needs to be controlled to enhance efficacy. To address these challenges, most recent research has demonstrated that extracts of tomato and potato byproducts, representative of Solanaceae as feedstock, have shown promising potential for biopesticides production [8]. As such, this paper provides a review of tomato and potato as feedstock for pesticide production, exploring their active components in the extracts and respective roles in pest control, extraction methods, and their future development in the hope of providing effective information to improve biopesticide production and application.

2 Tomato and potato by-products as feedstock for biopesticide production

Tomato and potato are representatives of Solanaceae which are a significant botanical group encompassing numerous economically vital plants. It was reported that global tomato production surged to 186.8 million metric tons in 2020 from 177.3 million metric tons in 2016. Projections indicate that the tomato market is poised to record a Compound Annual Growth Rate (CAGR) of 5.6% during the projected period of 2022–2027 [9].

Tomatoes (*Solanum lycopersicum*) are recognized as an abundant reservoir of phenolic compounds, pigments, antioxidants, and essential nutrients in human nutrition [10]. Research findings have demonstrated that extracts from tomato fruits possess antimicrobial and anticancer attributes [11–14]. Also, epidemiological studies suggest that the antioxidants in tomatoes decrease the chances of developing cardiovascular diseases [15].

In the industrial sector, waste is generated when tomatoes are processed into purees and juice [16]. Similarly, within the sphere of agribusiness, various components of tomato plants, including leaves, cuticles, peels, pulp, seeds, and stems, are either cast aside as unused outputs or employed as suboptimal fodder for livestock like cattle. This is a lack of economic advantages for tomato producers. These byproducts also containing bioactive substances are potential feedstocks for antimicrobial, antiviral, and antioxidant agents. Recently, there have been many studies on antimicrobial and antioxidant byproducts of plants. Now, it is a trend in the agricultural sector to reuse derivatives like peels, leaves, seeds, stems, and more. Research was conducted with the by-products of tomatoes on the contents of the bioactive components like steroidal alkaloids, total flavonoids, phenols, carotenoids, ketone, and chlorophyll [17]. The results show that the contents of the bioactive components are much higher in leaves than in other parts of byproducts including stem and root. The antibacterial activities of the tomato plant extracts were also investigated using two species of tomato named Pitenza and Floradade and concluded that bioactive contents and antimicrobial activity vary with distinct species, and leaves contain higher amounts of bioactive components than stem and root [17]. The leaves of the two varieties of tomato plant evaluated in this study showed the highest contents of tomatine and tomatidine with values of 4940 and 820 and 2430 and 225 mg/kg extract by Pitenza and Floradade, respectively. In addition, the leaf extracts of the two varieties exhibited the highest phenolic contents with values of 125,500 and 83,350 mg gallic acid equivalents /kg extract by Pitenza and Floradade, respectively [17].

In addition to tomatoes, potatoes (*Solanum tuberosum*) are extensively cultivated worldwide [18]. It possesses attributes like the ability to resist high heating temperatures during cooking or baking, a notable propensity for retrogradation, minimal thermal decomposition, and resilience against thermal and shear forces. Potato starch is commonly used by chefs when cooking and it has the lowest amylose content (important for small intestinal bacterial overgrowth, fungal and bacterial dysbiosis, and chronic inflammatory response syndrome) than other starch. Some of its importance include lowering cholesterol and stabilizing blood sugar. The potato starch market size is anticipated to have a growth rate of 3.5% and reach $4.9 billion in 2027 [19].

Like tomatoes, potatoes contain bioactive compounds such as glycoalkaloids (GA), α-chaconine, and α -solanine. The concentration of GAs in potato plants was found to be the highest in the cortex, blossoms, periderm, foliage, sprouts, green skin, and stems followed by the tuber and peels [20]. Another research on glycoalkaloids which analyzed the leaves of 18 potato varieties such as Lady Clair, Vivaldi, Diamant, Estima, Latona, Lady Rosetta, Caesar, Cantate, Lady Christl, and so on, shows that a high content of GAs was found in potato leaves though dependent on potato variety. Specifically, the total content of glycoalkaloids (TGA) varied. In expanding leaves, Lady Clair demonstrated a value of 30 mg per kg fresh weight (FW), whereas Vivaldi showed the highest value at 2669 mg/kg FW. Meanwhile, once leaves had fully expanded, Diamant contained a TGA content of 9 mg/kg FW, while Vivaldi, again, boasted a higher value at 2140 mg kg^{-1} FW. Furthermore, the peels of all different varieties contained glycoalkaloids, although not every variety harbored these glycoalkaloids in their flesh. Notably, varieties including Caesar, Lady Caesar, Lady Christi, Lady Clair, and Cantate did not possess any solanine or chaconine in their flesh. For the peels, the TGA range spanned from 80 to 569 mg/kg FW. It's interesting to note that peels encompassed about 73–97% of the total TGA present in the entire tuber. This is intriguing, given that peels constituted merely 9–12% of the total weight of the tuber in this study [21]. It is worth mentioning that earlier reports indicated that tubers have noticeably lower levels of glycoalkaloid content. This distribution is uneven, with higher concentrations detected in the periderm and cortex, which then experience a significant decline towards the pith [22]. The results show that potato foliage and tuber peels are important parts containing GAs. In the potato and processing industries, significant amounts of potato leaves and peels of tubers are generated. They are also another important source of producing biopesticides.

Based on the reported work on tomatoes and potatoes, it looks that the extracts of tomatoes contain higher amounts of bioactive compounds potential functioning as biopesticides. However, the amounts varied with specific species of tomatoes and potatoes.

3 Bioactive compounds in tomato and potato

In general, bioactive metabolites in potato and tomato relevant to pesticidal activities include steroid alkaloids, flavonoids, phenolics, ketones, and additional components [23]. In humans, all these compounds have nutritional and pharmacological functions, and they are also involved in host-plant defenses. More details about the above-mentioned bioactive compounds are described as follows.

3.1 Glycoalkaloids

Glycoalkaloids (GAs) possess antimicrobial and pesticidal properties [20]. Plants belonging to the *Solanum* genus (Solanaceae) are a common source of glycoalkaloids. Among these plants are important crops like potatoes *(S. tuberosum),* tomatoes *(S. lycopersicum),* and eggplants *(S. melongena).* Glycoalkaloids are a type of steroidal glycosides containing nitrogen, and they have an amphiphilic nature due to their dual structural components. The initial component, known as aglycones, is a hydrophobic 27-carbon cholestane skeleton with fused nitrogen in the F ring. The second part is a hydrophilic carbohydrate side chain that links to the 3-OH position (Fig. 1). Naturally occurring glycoalkaloids are called α-compounds. The sugar chains can undergo hydrolytic cleavage through enzymatic or chemical processes [9].

Solanaceae plants produce two main glycoalkaloids, each distinct from the species within the Solanaceae plant. In tomato plants, they are α-tomatine and dehydrotomatine while in potato plants, they manifest as α-chaconine

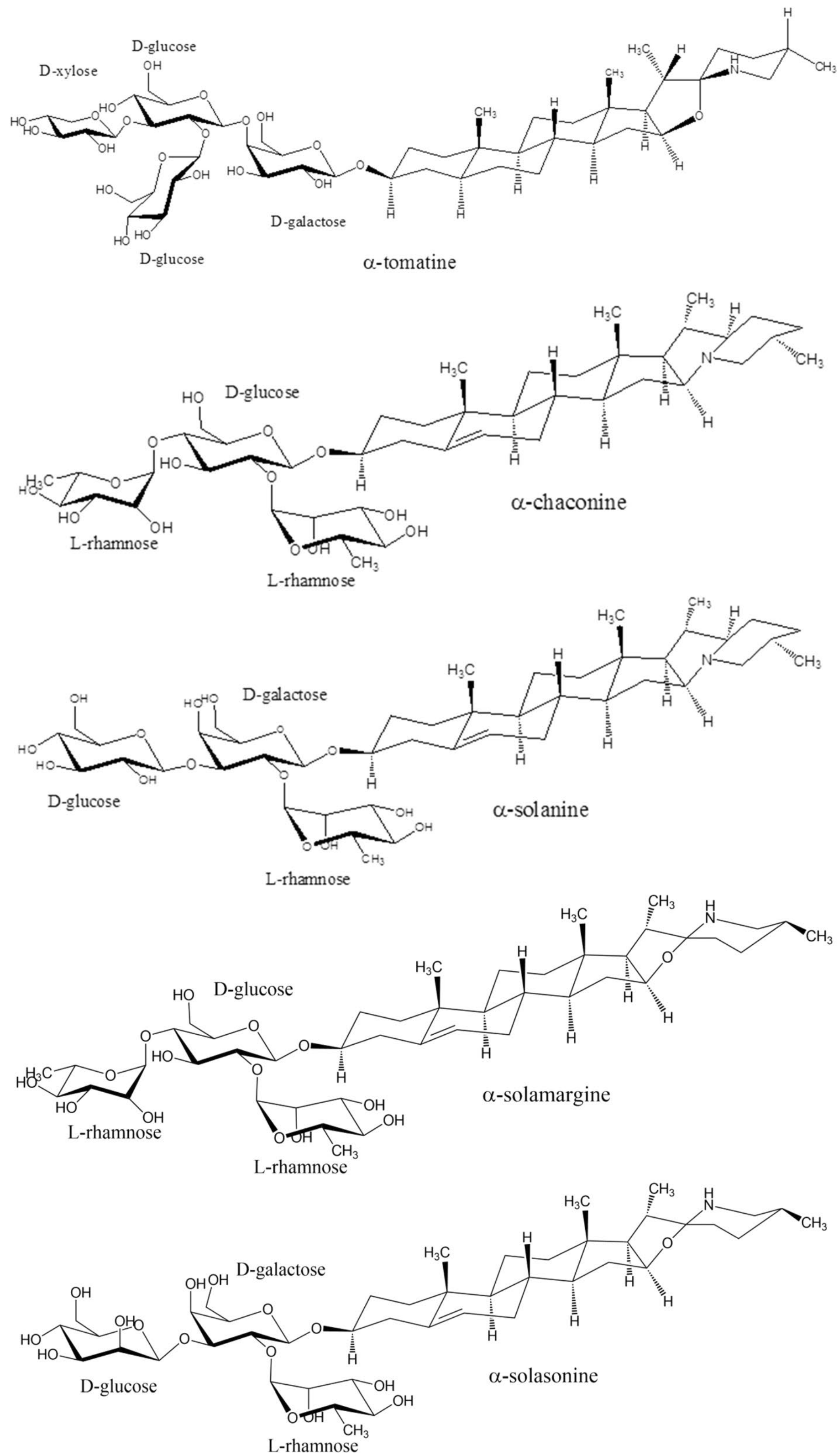

Fig. 1 Morphological imagery of glycoalkaloids such as α-tomatine, α-chaconine, α-solanine, α-solamargine, and α-solasonine [24]

and α-solanine [25]. The initial glycoalkaloid discovered in potatoes was α-solanine, reported as a natural component between 1826 and 1954 [20]. Subsequently, α-chaconine and later α-tomatine were identified in 1948. Among these, tomatine is a major alkaloid that consists of two natural constituents: the aglycone tomatidine and a residual tetrasaccharide containing d-xylose, d-galactose, and two units of d-glucose. Although glycoalkaloids are not essential for plant growth and functionality, they play a crucial role in plant defense against pests and pathogens [20]. Both tomato and potato glycoalkaloids exhibit diverse biological activities, defending against viruses, fungi, bacteria, and inflammation, and lowering cholesterol. Additionally, investigations into the impact of *Pseudomonas syringae* on phenolic extracts from tomato leaves have revealed that the extent of microbiological contamination influences the augmentation of phenolic compounds. This phenomenon serves as a responsive mechanism when the leaves come under attack from microorganisms [26].

Glycoalkaloids have demonstrated various degrees of toxicity dependent on concentration to a broad spectrum of organisms ranging from fungi to humans [20]. Numerous investigations underscore that altering the structure of both carbohydrate and aglycone portions significantly influences glycoalkaloid bioactivity [20]. Other minor glycoalkaloids found in trace amounts were also documented, although their precise quantities relative to major glycoalkaloids (α-chaconine for potatoes and α-tomatine for tomatoes) could only be approximated [20]. Potato extracts revealed scant amounts of minor glycoalkaloids, including solanidadienol solatriose (11.7–1.6%), dehydrosolanine (1.2–9.8%), leptinine I (6.2%-0.6%) together with an isomer of α-solanine (1.5 ± 0.2%), and an isomer of α-chaconine (9.6 ± 1.4%). Dehydrochaconine (52.4 ± 2.5%) and solanidadienol chacotriose (40.0% ± 2.2%) stood out as the most prominent minor glycoalkaloids present in the sample [27]. They share the same glycosidic group as α-chaconine (chacotriose) but differ in aglycones.

It was reported that glycoalkaloids (GAs) exhibited not only deadly effects but also a variety of damage at various levels of biological system [20]. The toxicity brought about by GAs is linked to their ability to disrupt membranes and hinder acetylcholinesterase activity. Existing literature illustrates that the effectiveness of these compounds relies on their configuration, and cooperative effects when the primary GAs extracted from potatoes are used for experiments [20]. Additionally, the biological strength is contingent on the ratio of the GA mixture employed. The proportions of α-chaconine and α-solanine present in potato plants differ based on the cultivars, tissues, and growth conditions.

Glycoalkaloids detected in tomato leaves are like solanine, but the presence of toxic glycoalkaloids is typically not discernible in the fruit [28]. Friedman's research found that tomatine has a strong ability to bind with cholesterol. This has led to the belief that the limited oral toxicity of tomatine might stem from its capacity to form an insoluble complex with cholesterol within a living organism, subsequently being expelled through fecal matter [29]. Similarly, Kozukue suggested that the production and breakdown of dehydrotomatine and tomatine in tomato (*S. lycopersicum*) leaves could be regulated by different genetic processes. The findings indicated that the concentrations of tomatine ranged from 209.4 to 925.6 mg/100 g and tomatidine from 25.0 to 110.4 mg/100 g [23].

3.2 Flavonoids

Another major bioactive component is flavonoids, which constitute a group of phenolic compounds. These include nonvolatile plant metabolites such as chalcones, anthocyanins, flavonols, flavanones, and flavones [30]. Flavonoid compounds have been reported to exist within tomato plants, primarily in the leaves, where they coexist with hydroxycinnamic acid [31].

Flavonoids include a subclass known as flavonols. This subclass comprises compounds such as kaempferol, quercetin, and myricetin. Flavonols demonstrate efficacy in scavenging radicals and have the potential to function as antioxidants that interrupt lipid oxidation reactions. They abundantly existed in tomato leaf extracts. Kyung and colleagues undertook a study to explore the flavonol contents, glycoalkaloids, and antioxidant properties of leaf ethanol extracts from different tomato strains [32]. Using high-performance liquid chromatography with a diode array detector, they identified five flavonols, two glycoalkaloids, naringenin, and tomatine in significant concentrations. High levels of quercetin, kaempferol, and tomatine were observed in some species, contributing valuable data to the chemical profile of tomato leaves. However, there is another report that indicates that tomatoes contain lower levels of flavonoids compared to other vegetables [33].

3.3 Phenolics

In addition to steroid alkaloids and flavonoids, plants harbor a diverse array of phenolic derivatives crucial for both reproduction and plant growth. Phenolic compounds serve as natural pesticides and antibiotics, doubling as innate antioxidants distributed throughout all plant components. Studies have demonstrated a direct link between heightened concentrations of total phenolic compounds and enhanced antimicrobial efficacy [34]. Smirnova and the team supported this finding, demonstrating a positive correlation between elevated polyphenol levels and potent antimicrobial activity against *E. coli* [35]. Furthermore, phenolic compounds function as antioxidants that protect lipids from oxidative damage, enhancing the nutritional quality of food. Additionally, these compounds partake in a broad spectrum of biochemical activities, including anticarcinogenic, antioxidant, and antimutagenic properties [24].

3.4 Methyl ketones (MKs)

They are another group of bioactive components that are alternatives to synthetic acaricides. High levels of methyl ketones are synthesized and accumulated on the leaves of wild tomatoes because of *Solanum habrochaites* (Solanaceae) or glandular trichomes. Other bioactive compounds carotenoids such as lycopene along with others were also found in tomatoes. Lycopene can interact with other compounds to safeguard human health [36].

The potential of employing MKs as substitutes for synthetic acaricides in managing the *Tetranychus urticae* Koch, commonly known as the two-spotted spider mite, has been assessed [6]. To alter the fertility of these spider mites four different MKs were used (namely, 2-pentadecanone, 2-dodecanone, 2-undecanone, and 2-tridecanone), both individually and in combinations, to assess their repellent and inhibitory properties. Extracts from tomato leaves were formulated in ethanol and applied via spraying. The outcomes revealed the resilience of all MKs against spider mites. After 4 and 24 h, the average egg count per female mite on bean leaf discs diminished from 0.8 to 0.3 and 0.9 to 0.3, respectively, representing reductions of 65% and 68%. Furthermore, when tomato leaf extracts were obtained using water, the egg count per female mite declined from 1.7 to 0.7 after 4 h and from 2.6 to 0.9 after 24 h which indicates reductions of 60% and 67% [6]. Furthermore, the study revealed that spider mites exhibited the highest sensitivity to 2-tridecanone (with an LC50 of 0.08 μmol cm^{-2} of treated leaf surface) and the lowest sensitivity to 2-undecanone (with an LC50 of 1.5 μmol cm^{-2} of treated leaf surface) after 4 h of treatment [37].

In another study conducted with tobacco hornworm, *Manduca sexta* L, the findings demonstrated the effectiveness of methyl ketones, specifically 2-dodecanone, 2-tridecanone, and 2-undecanone, against this pest. Notably, 2-tridecanone was identified as effective not only against tobacco hornworms but also against adults of the green peach aphid. Among the methyl ketones, 2-tridecanone stood out as the most potent in combating the tobacco hornworm and tobacco budworm, *Heliothis virescens* Fabricius (with an LC50 of 0.015 μM cm^{-2}) [6]. However, 2-tridecanone is a volatile compound. Stabilizing it during application is important to ensure the effectiveness of the biopesticide.

3.5 Extract or mixture of bioactive compounds

Pure substances hold scientific fascination due to their potential as foundations for novel classes of synthetic insecticides [38]. Conversely, compound mixtures in the form of extracts, which are easier to obtain, exhibit synergistic interactions and more effective pest control. Consequently, the employment of fewer substances in agrochemistry might be viable compared to using individual pure compounds. This positions them as promising alternatives to commercial pesticides, particularly in developing nations. Owing to the cooperative actions of plant-included substances, isolated metabolites frequently manifest milder impacts in contrast to the amalgamation of unadulterated alkaloids and plant extracts.

The effects of sublethal concentrations of tomato leaf extracts on *Spodoptera exigua*, an investigation was conducted. According to the work [39], the results show no indications of immediate lethal effects. The extract influences midgut and fat body cells. While alterations in midgut cells were minor, fat body cells displayed conspicuous changes, including fusion of fat droplets, mitochondrial vacuolization, endoplasmic reticulum swelling, and nuclear envelope expansion. These effects were even more pronounced at the highest concentration, particularly among groups exposed to potato extracts as opposed to tomato extracts [39]. Whereas a separate investigation, employed concentrations of 250, 500, 750, and 1000 ppm, with mortality rates rising alongside concentration levels to manage aphid infestation using tomato plant leaves [40]. To extract the useful compounds from tomato leaves, the leaves are first dried and ground into a fine powder. This powder is then soaked in a mix of hexane, acetone, and ethanol for a week. After soaking, the mixture is filtered, and the solvents are evaporated to get the crude extract, which is stored in a freezer. When it's time to use the extract, it's diluted to different concentrations and sprayed on aphids to test its effectiveness as a pesticide. The mortality rate was 27.5% at 250 ppm, escalating to 80% at 1000 ppm. In addition, using Gas Chromatography-Mass Spectrometry (GC/MS) for characterization of the chemical composition of tomato extract shows a major compound, phytol (16.03%), and the presence of forty-five other compounds.

Under controlled laboratory conditions, an investigation was carried out to assess the toxicity levels of a mixture of solanaceous glycoalkaloids against stored grain insects [41]. Segregation and separation were done for the total glycoalkaloids (TGAs), α-tomatine from tomatoes, *Lycopersicon esculentum Mill,* and α-chaconine and α-solanine from potatoes, *S. tuberosum* L. Then the rice weevil, *Sitophilus oryzae* L. *Coleoptera: Curculionidae* and the rust red flour beetle, *Tribolium castaneum* Herbst *(Coleoptera: Tenebri-onidae)* were subjected to toxicity assessment. Findings show that the tested glycoalkaloids are significantly toxic against the target insects. The residue of glycoalkaloids was applied to fully grown rice weevils for assessment, with TGAs demonstrating the highest level of toxicity, followed by α-solanine, α-chaconine, and α-tomatine. Similarly, when considering the rust-red flour beetle, the toxicity hierarchy from most to least toxic was TGAs, α-chaconine, α-solanine, and α-tomatine. With these results, it is recommended to use glycoalkaloids of Solanaceae on stored grains as a form of protection from insect infestation [41]. In addition, the structure of imagoes was investigated on exposure to potato extracts, there was evidence of wing malformations (Fig. 2a–f).

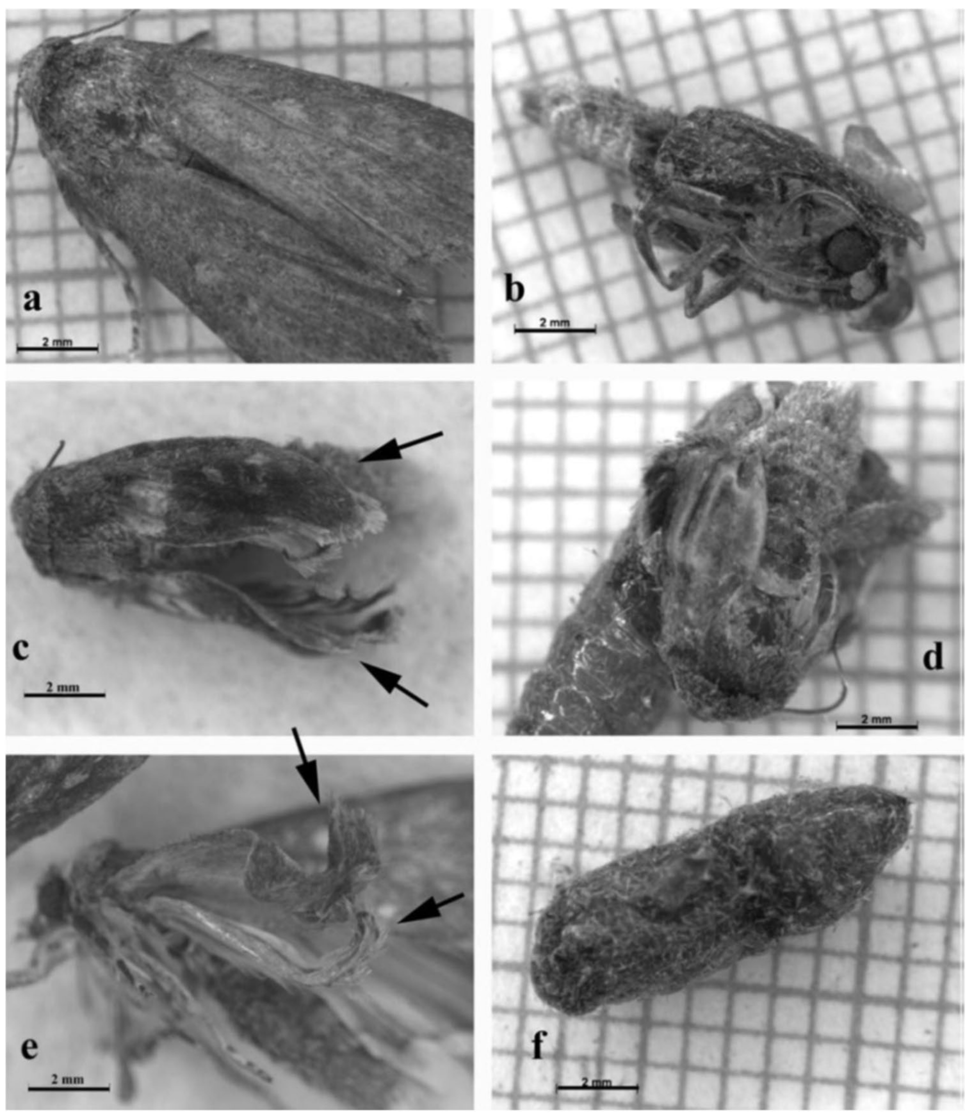

Fig. 2 Structural deformations of moths on exposure to potato extract shows, **a**—control imago; b—dead imago pupate dosed with 5,000 ppm; **c**—an imago dosed with 50 ppm with deformed wings (black arrows); **d**—dead insect during imaginal molt dosed with 500 ppm; **e**—deformed wings of imago on exposure to 5000 ppm (black arrows); **f**—a pupa dosed with 50 ppm [39]

Another research study further validates the effectiveness of a mixture of bioactive compounds. The study focused on investigating the nonlethal developmental effects of *S. exigua* Hubner [39]. The moths fed on a myriad of plants such as potatoes, tomatoes, beans, soybeans, pepper, onion, corn, cabbage, eggplant, and tobacco. Acute toxicity was observed when *S. exigua* larvae were exposed to the two tested extracts. There was no noticeable decrease in the body mass or T_{50} within the exposed groups. Moreover, tomato extracts show a decreased body mass compared to potato extracts. Upon the introduction of the examined extracts, a comparable pattern was noted concerning the success of larval hatching when nourished with a specific diet. Additionally, when extracts of potato leaf were exposed to *S. exigua,* the hatching success was significantly lower compared to the control, while tomato leaf extracts exhibited a slight reduction in the quantity of hatched larvae. Nonetheless, all the observed effects did not depend on the level of concentration used. This observation was also noticeable for pupae exposed to assessed extracts.

In a broader context, numerous studies have documented sublethal impacts such as growth inhibition, deformities, repulsion, and deterrent effects, alongside instances of acute toxicity [42]. Again, it has been noted that individual metabolite often exhibits less pronounced effects compared to combinations of pure alkaloids or plant extracts, possibly due to the synergistic interactions among the compounds found in plants. The outcomes are contingent on factors such as the specific plant species and the type of insect being assessed. Variations in effects can stem from the insect's diet, its life cycle, or its developmental phase. It has been observed that extracts tend to be more poisonous to genera that are not considered pests of economically significant plants, such as *Galieria or Aedes* [42]. Consequently, it is imperative to conduct thorough investigations into the efficacy of plant extracts before their application in agriculture.

4 Extraction and analysis methods

Solvent extraction is a popular way to extract bioactive compounds, where the choice of solvent plays a key role in determining the yield and composition of the molecules. Solvents that match the polarity of the target compounds generally lead to more effective extractions [43]. Additionally, there is a growing trend toward using environmentally friendly solvents derived from renewable resources such as supercritical fluids, water, terpenes, and so on. In general, raw materials such as the leaf, stem, and other parts of potato or tomato are usually dried mostly at 40 °C where in some cases, a vacuum is applied [17], then ground into smaller particles in the range of desired sizes. Afterward, the particles will be mixed with solutions containing organics such as 75% ethanol, 82% methanol, or chloroform. In the case of extracting GAs, acetic acid is being used. The extraction process is done at 27 °C or 70 °C, then the mixture is filtrated and the remaining solvents on the filtrates are removed by evaporation. Finally, the extracts are stored at − 20 °C. The detailed extraction conditions and references can be found in Table 1 below. The bioactive components are analyzed using various methods. High-Performance Liquid Chromatography (HPLC) is used for the analysis of GAs and other bioactive components by spectrophotometer and additional methods. The examples of the analytical methods are also summarized in Table 1.

5 Advantages and challenges of using tomato and potato leaf extract as biopesticides

Biopesticides derived from tomato and potato leaves have several merits such as they are not harmful to non-target organisms and are environmentally friendly which makes them suitable for pest control over commercial pesticides [44]. They exhibit cost-effectiveness, offering a more economical option when contrasted with chemical fertilizers. Additionally, they pose no contamination threat to water sources and avoid contributing to bioaccumulation. This sustainability aspect has propelled the adoption of biopesticides within the agricultural domain [28, 44]. Their increasing utilization is attributed to their ability to diminish the requirement for traditional pesticides. This is a result of their potency in small quantities and their rapid decomposition, which minimizes the persistence of harmful residues [45].

As previously stated, biopesticides make up a minor portion of the overall global crop protection market due to factors such as expenses, impacts on pest issues across various cropping methods, and other considerations. The major challenges are presented as follows.

5.1 Cost

The biopesticide development from tomatoes, potatoes, and other biological sources often involves high costs due to extensive research, low concentration of biopesticide compounds in the plant parts, and need for specialized production

Table 1 Extraction conditions and analytical methods of bioactive components in tomato and potato

Plant Name	Parts	Extracted Component	Extraction/Analysis method	Ref
Tomato	Stem, leaf, whole plant, or fractions	Glycoalkaloids, total phenolic, flavonoids,	Extraction: Dried specimens were combined with ethanol and 5% acetic acid solution in a ratio of 95:5. The mixture was continuously stirred for 72 h at room temperature. The resulting liquid was then concentrated through evaporation and preserved at 20 °C for future use. Analyses: Glycoalkaloids: HPLC Total phenolics: Spectrophotometry Flavonoids: Spectrophotometry	[17]
Potato *(Solanum tuberosum)*	leaf	Crude glycoalkaloids	Dry powdered leaves were macerated in 95% ethanol acidified with 5% acetic acid. The resulting filtrate was evaporated, and the residue was acidified with 3 ml acetic acid, then alkalined with 25% NH_3 to obtain a precipitate. This precipitate was further purified by treatment with concentrated ammonia, followed by crystallization from ethanol (C_2H_5OH). Analyses: Crude glycoalkaloids: Medium Pressure Liquid Chromatography (MPLC)	[41]
Potato *(Solanum tuberosum)*	leaves	α-chaconine and α-solanine	The method mentioned above was employed to extract the raw glycoalkaloids, which were subsequently filtered and precipitated. The resulting precipitate was then separated into fractions using medium-pressure liquid chromatography with a mixture of $CHCl_3$, MeOH, and 2% NH_4OH. The fractions were analyzed using thin layer chromatography (TLC) technique. Analyses: α-chaconine and α-solanine were obtained by Nuclear Magnetic Resonance (NMR) and Mass Spectrometry.	[41]
Tomato *(Lycopersicon esculentum)*	leaves	α-tomatine	Following the previously described procedure, crude glycoalkaloids were first prepared and isolated through crystallization. These isolates were then subjected to chromatography on TLC plates using a solvent mixture of ethyl acetate, methanol, and concentrated NH_4OH in a 4:5:1 ratio	[41]
Potato *(Solanum tuberosum L*	Peel, leaves, flesh	α-solanine and α-chaconine	Samples of peel, leaves, and flesh were treated with a mixture of 20 mL water, acetic acid, and sodium bisulfite ($NaHSO_3$) in a 95:5:0.5 ratio. The mixture was subjected to vacuum filtration and centrifugation, then passed through a sequence of solvents: 5 mL of acetonitrile, 5 mL of a water–acetic acid–$NaHSO_3$ mixture, and finally 4 mL of a water–acetonitrile mixture in an 85:15 ratio Analyses: α-chaconine and α-solanine: HPLC	[21]
Tomato *(Lycopersicon esculentum)*	Leaf	Methyl ketones Trans-caryophyllene	Leaflets were mixed with 100 ml of chloroform and extracted using n-hexane and ethanol. The resulting filtrate was evaporated and streamed using nitrogen gas. Analyses: Methyl ketones and trans-caryophyllene were obtained using HPGC equipped with a mass spectrometer and automatic injector.	[6]

Table 1 (continued)

Plant Name	Parts	Extracted Component	Extraction/Analysis method	Ref
Tomato *(Lycopersicon esculentum)*	Leaf	Flavonol aglycones Steroids Glycoalkaloids Total polyphenols	Dried tomato leaves were extracted with 40 mL of 75% ethanol under a nitrogen atmosphere, followed by drying using a vacuum concentrator to obtain crude extracts Analyses: Flavonol aglycones: HPLC Steroids glycoalkaloids: HPLC Total polyphenols: Spectrophotometry	[32]

methods. Compared to traditional chemical pesticides, which are manufactured at large scales with well-established processes, biopesticides may lack the economies of scale, making them more expensive to produce. For example, producing tomatine as a biopesticide involves several costly steps, starting with the screening process to identify optimal formulations and concentrations of tomatine for effective pest control. The compound must be carefully isolated and purified from tomato plants, a process that can be resource-intensive and time-consuming. Once isolated, formulating tomatine into an effective and stable biopesticide requires additional investment in research to determine the most suitable delivery methods (e.g., sprays, granules) and to ensure the stability of tomatine under different environmental conditions such as soil temperature, pH, humidity, and so on. This higher cost can discourage widespread adoption by farmers, especially in regions with limited access to funding or resources [46–48].

5.2 Effectiveness limited to specific pests

The effectiveness of biopesticides is limited to specific pests, meaning their narrow spectrum of activity [3, 49]. This makes them less versatile than traditional chemical pesticides being capable of targeting a broader range of insects and pathogens. The specificity of biopesticides to certain pests can cause farmers to be somewhat restrained in their utilization. For instance, while tomato extracts may be effective against moth, or aphids infections, it may have limited efficacy against other pests like mites or root-damaging nematodes. As a result, farmers might face challenges in using tomato extracts alone for comprehensive pest control and may need to use additional pest management strategies, which can complicate and increase the cost of pest control programs.

5.3 Regulatory hurdles

Biopesticides must undergo rigorous regulatory approval processes before they can be marketed, which can vary widely between countries. These regulations often require extensive safety and efficacy testing to ensure that the biopesticides will not harm humans, animals, or the environment. The approval timeline can be long, and the regulatory framework may be complicated or unclear, particularly in emerging markets, which slows down product development and commercial release [50].

5.4 Stability and shelf-life of biopesticide

One of the challenges in developing biopesticides is ensuring that the active ingredients, whether they are plant-based, microbial, or natural compounds, remain stable under various environmental conditions. Biopesticides may be sensitive to factors such as temperature, light, and humidity, which can lead to degradation of their efficacy. Stability issues must be addressed to make the products reliable for use over time. Related to stability, the shelf-life of biopesticide products is critical for their commercial success. Lifespan and field efficacy of biopesticides are limited because of changes in soil conditions, humidity, and temperature [46–48]. Many biopesticides, particularly those derived from natural sources, can have a short shelf-life, meaning they lose potency or become ineffective over time. Effective preservation techniques need to be developed to extend the shelf-life of these products, making them more appealing to farmers and distributors who require products with a longer period of usability.

6 Future development/prospects

Researchers have done some work on the insecticidal application of biopesticides [51, 52]. But in general, the number of related studies is still relatively lacking. The research on synergistic effects of extracts from agricultural byproducts, the mechanism of bioactive compound action, and extraction and application methods of biopesticides need to be further enhanced.

6.1 Explore potential synergies

To explore potential synergies between tomato and potato extracts and other biopesticides or farming practices provides a promising opportunity to enhance the efficacy and sustainability of pest management strategies. Combining tomato and potato extracts, containing bioactive compounds like tomatine and solanine, with beneficial microorganisms or other plant-derived compounds could lead to synergistic effects, where the combination of substances enhances the overall pest control performance [50, 53].

6.2 Integration with farming practices

In addition, integration of these biopesticides with innovative farming practices, such as crop rotation, intercropping, or integrated pest management techniques, could maximize their efficacy. By using tomato and potato extracts in combination with other biological pest control methods, farmers could reduce pest resistance, enhance biodiversity, and maintain soil health, leading to more sustainable agricultural practices [50, 53, 54].

6.3 Nanotechnology and synthetic biology

Moreover, emerging nanotechnology could further improve the efficacy of biopesticides. It could enable the development of nano-sized delivery systems that protect the active compounds in tomato and potato extracts, enhancing their stability, uptake, and targeted delivery to pests. This could improve the longevity and potency of the biopesticides, making them more efficient in the field [55]. Similarly, synthetic biology could be used to engineer microorganisms or plants to produce higher concentrations of pest-fighting compounds, or to enhance the stability of these compounds under varying environmental conditions [54, 56].

By exploring these innovative approaches, the field of biopesticide development could see significant advancements, offering farmers more effective, environmentally friendly, and sustainable pest control options.

7 Conclusion

The use of biopesticides over commercial pesticides has a lot of benefits. Agricultural byproducts such as tomatoes and potatoes provide diverse sources for producing biopesticides. They contain bioactive compounds such as glycoalkaloids, flavonoids, additional phenolics, ketones, and additional components relevant to pesticide activities. Extract or mixture of the bioactive compounds are easier to obtain from the raw agricultural byproducts and demonstrate more effective pest control because of synergistic interactions compared to individual pure compounds. Unlike conventional pesticides which aim to outrightly eradicate pests, biopesticides adopt a distinct approach by incorporating a pest management system that gradually curbs insect populations over time. Rather than directly exterminating insects, biopesticides typically employ indirect mechanisms to achieve control. Despite these advantages, it is important to weigh the drawbacks such as increased costs and limitations of using the biopesticides. A comprehensive evaluation of their effectiveness in addressing specific pest issues within various crop systems, exploring potential synergies, integrating with farming practices, and incorporating with nanotechnology and synthetic biology are expected to lead to advancement and necessitate extensive field research. Above all, prioritizing biopesticides can benefit society and the agricultural sector in the times ahead.

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Declarations

Ethics approval and consent to participate This is not applicable as no human or animal specimen was used.

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