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Chapter

Advances in Postharvest Disinfestation of Fruits and Vegetables Using Hot Water Treatment Technology-Updates from Africa

Shepard Ndlela, Nelson L. Mwando and Samira A. Mohamed

Abstract

Hot Water Treatment (HWT) provides adequate phytosanitary assurance that treated fruits and vegetables exported abroad are free from devastating quarantine pests. Two systems for HWT are currently available for commercial use namely the batch/jacuzzi and the continuous flow system depending on user requirements. Several protocols have been developed the world over and a few in Africa, but adoption has been lagging because of various factors chief among them lack of large scale validations of experiments to guide application at the commercial level. Mango, Bell pepper, avocado, and French beans play an important role in the livelihoods of people in Africa. However, their export is constrained by pests such as the invasive Oriental fruit fly, the false codling moth, and thrips. To circumvent this issue, disinfestation HWT protocols have been developed which seek to provide quarantine assurance to lucrative export markets. Hot Water Treatment technology has several advantages over other conventional phytosanitary treatments. It provides a triple function of cleaning, disinfesting, and disinfecting and is friendly to users, consumers of the treated commodities, and the environment. We discuss HWT in the context of its future and applicability in Africa. It is the future of postharvest treatments.

Keywords: Export, Mango, Preharvest, physiologically mature, Sap, Lucrative export markets, Interceptions, Quarantine, Phytosanitary, Biochemical, Physical parameters

1. Introduction

Fruits and vegetables contain important nutrients which make them vital components of a balanced diet essential for healthy living [1]. Several studies have been conducted worldwide, on the diseases and deaths occurring as a result of lack of vegetable and fruit consumption [2, 3]. Health and nutrition constitute an impending global catastrophe if clear action steps are not taken to contain the threat. The FAO reports that a staggering 38% of the world's population cannot afford the cheapest healthy meal, and for those able to at least access a healthy meal, 19% consume meals with inadequate nutrients [4].

Fruits are important sources of nutrients, minerals, and antioxidants necessary for energy, body repair, and growth as well as regulation of physiological processes [5]. The demand for fruits and vegetables is increasing globally, especially in the developed countries due to the increased push for healthy diets than just quantities [6]. The developed world has a huge deficit of fruit and vegetable supply and must supplement this with imports from the developing world such as Asia and Africa. It is estimated that the developing world produces 98% of the world's fruit production and the high-income countries in the west import over 80% of this quantity [4]. On a positive note, fruit production is rising steadily in Africa, with millions of growers at the smallholder level contributing significantly to national yield [7, 8]. Africa is endowed with a variety of indigenous fruits and imported exotic varieties cultivated for both the local and export markets [9]. However, the export of these fruits and vegetables is constrained by stringent export requirements mainly by the USA and European Union (EU). These requirements safeguard the possible entry and spread of harmful pests into areas where they are absent and will cause devastating effects once established. Upon being received at ports of entry, most fruits and vegetables are expected to be accompanied by a relevant certification from the exporting country and are then subjected to phytosanitary inspections. If the exported commodity is found to be infested by insect pests considered to be quarantine or regulated in nature, the consignment is rejected and destroyed at the exporter's cost.

The EU has major regulations that govern imports against quarantine and regulated pests such as the Regulation (EU) 2016/2031 and the Commission Implementing Regulation (EU) 2019/2072 [10, 11] among various other amendments and directives. The USA is a major player in the import of fruits and vegetables and has several federal orders and directives issued under the Plant Protection Act –7U.S.C. 7701 et seq- [12] to protect against the entry of foreign injurious pests. In addition, all countries through their National Plant Protection Organizations (NPPOs) are bound by various international standards for phytosanitary measures to abide by fair practices when exporting commodities e.g. ISPM 20 offers guidelines for an import regulatory system [13].

Though effective pre-harvest management techniques for pests of fruits and vegetables are widely available, they are unable to confer 100% freedom from infestation. In this regard, postharvest treatment technologies can provide quarantine assurance and allow exporters to meet export requirements and satisfy the growing international demand for fresh fruits and vegetables [14]. Various postharvest treatment technologies are available for adoption in providing quarantine assurance that fruits and vegetables are free from devastating pests not found in importing countries. These include controlled atmospheres [15], irradiation [16] Vapor Heat Treatment (VHT) [17], cold treatment [18], and immersion Hot Water Treatment (HWT) [19, 20] among others. Though the treatments may achieve the objective of disinfecting and disinfesting fruits and vegetables, they are also known to affect the physical and chemical properties of treated commodities [21]. This chapter explores HWT with a specific focus on Africa and applications aimed at satisfying requirements by lucrative export markets such as the USA and the EU. Prospects for commercial application of HWT on mango, avocado, bell pepper, and French beans are discussed.

2. Constraints to export necessitating HWT technology

Data on the loss of export earnings in most African countries is scarce due to poor coordination, lack of financial resources to conduct systematic studies, and lack of standard indicators for measurement of loss in mixed production cropping systems and value chains. Currently, most African countries are not exporting or are exporting under fear of interceptions. Following the invasion of Africa by the devastating polyphagous fruit fly *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), [22] the USA through an emergence Federal order restricted the movement into the USA of fruits and vegetables deemed to be hosts of the pest [23]. The fruits and vegetables were only to be granted entry if they were originating from a country free from *B. dorsalis*, grown under a structure that excludes pests as certified by the USA systems approach 7CFR319.56, or having been subjected to an approved treatment [23]. The list of hosts was updated in 2015 through another Federal order DA-2015-2054, making exports nearly impossible for African countries where the pest continues to spread rapidly. Recently the EU announced new regulations on mango imports, through directive (EU) 2019/523 of 21 March 2019 which largely affects developing countries particularly from Africa where both pre-and post-harvest systems are absent or poorly developed. The directive stipulates that for mangoes to be accepted in the EU, the consignment must originate from a country free from quarantine fruit flies, a pest-free area, or a pest-free production site or show empirical data that is effective postharvest treatment has been administered [24].

To this effect, several countries have suffered losses in potential export earnings due to the unavailability of postharvest treatments that would allow them to export mango, either regionally or internationally. For example, as a way of protecting the vast fruit production industry in South Africa, from the *B. dorsalis* menace at the height of the incursion, the government halted the importation of fruits from Mozambique resulting in the former Portuguese colony suffering a USD 2.5 million revenue loss [25]. A single export company in Mozambique reported losses of USD 1.5 million per year due to restrictions on exports of fruits and vegetables from Mozambique [26]. Kenya similarly lost USD 1.9 million worth of export earnings due to an import ban imposed by South Africa [27]. In West Africa, potential export losses due to *B dorsalis* are estimated at USD 220 billion per annum [28]. This is huge considering that millions of families derive their livelihoods from the various value chains in the fruit and vegetable production sector.

The recent insurgency by the native invasive False codling moth (FCM), *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) has also resulted in thinning of export markets due to quarantine restrictions [29]. The pest threatens the production of avocadoes, capsicum, citrus, and various solanaceous crops. The FCM is highly polyphagous, and is native to Africa but is known to occur in Israel [30, 31]. Interception of commodities at ports of entry is on the rise with pests having been intercepted several times in the USA but with no record of establishment [32]. There are also fears that it could invade Europe, thus restrictions have been heightened by the EU [33]. Through the European Commission Implementing Directive 2017/1279, the new regulations require that capsicum be exported from pest-free areas or be subjected to an effective treatment before export. A systems approach of managing these devastating pests is not sustainable in fragmented production systems as has been mentioned afore, and similarly, growing these crops under protected environments is expensive and beyond the reach of resource-poor smallholder growers in Africa, leaving the option of postharvest treatment as the most feasible and efficient approach because it can be done by medium to large scale commercial enterprises.

2.1 Hot water treatment technology

Hot Water Treatment technology particularly immersion, involves subjecting fruits or vegetables to hot water at a specified temperature and duration beyond the thermal limits tolerated by the various stages of development for pests of interest. The temperature and duration used are often that which kills the most thermotolerant stage of development. The preference for HWT emanates from the fact that it is an efficient system in heat transfer to treated commodities than for example air due to its capacity to conduct heat [34]. It may not need specialized structures except for temperature regulation, water circulation, and a simple vessel to hold water during treatment which makes it ideal even for small-scale applications [21]. Furthermore, HWT performs a dual function of disinfecting and disinfecting in one treatment.

Immersion HWT is not new in phytosanitary treatment spheres. Historically it was mainly used in killing pathogens on fruits but has since found new applications in killing insect eggs and larvae on or in fruits [35]. Protocols to disinfect and disinfest different commodities of economic value have been developed in various countries worldwide [28, 36]. Some of the protocols developed for mango, bell pepper, and avocado at the international level (**Table 1**) have been instrumental in guiding similar research in Africa where the three commodities have the potential to boost foreign earnings significantly if exported to lucrative markets. The HWT technique has become an integral alternative for postharvest treatments due to the demand for non-chemical treatments against pestiferous insects and pathogens [35]. Consumers are increasingly becoming aware of their health and progressively seek alternatives for treatments whose effects are presumably unknown at present, or are shrouded in mystery and conspiracy theories. The technique is equally important as a forerunner of other treatments for example HWT has been shown to decrease the effects of cold treatment on fruit and vegetables [54]. Commodities which are mostly exported in refrigerated containers overseas for long periods are sometimes susceptible to cold injury, hence short periods of immersion in HWT induce some level of tolerance to cold and increases quality and shelf life [59]. In bell pepper, heat treatment increases the levels of polyamines which are responsible for reducing cold injury and decay, thus allowing the capsicum to be stored for longer periods than would be possible when subjected to cold treatment alone [54].

The ecotoxicological effects [both known and unknown] of various chemicals used in postharvest treatments or their excessive use at preharvest meant to produce clean fruits without the need for postharvest treatments have also caused a renewed interest in HWT. Some chemicals from treatment effluent or evaporation are known to stress ecological systems leading to irreversible damage [60]. At the body level, exposure and effect regarding the endocrine, reproductive and other systems are known to be current concerns and emerging issues [61]. Hot Water Treatment technology offers a non-chemical system of treating fruits and vegetables which is friendly to the users, consumers, and the environment.

Treatments aimed at disinfecting, by cleaning with pure water, fungicide, bleaching liquids, or some generally recognized as safe (GRAS) compounds are often for short periods [62, 63]. Those aimed at disinfecting or assuring freedom from quarantine or regulated insect pests take long periods usually up to one hour or more [35, 64].

2.2 Requirements for HWT

In most countries where HWT is practiced, the design of the treatment machine and the entire facility is chosen by the individual or company wishing to treat fruits and vegetables. The current technology uses the batch/jacuzzi system, the continuous flow system (CFS) [65], and the drainage system [66]. The continuous flow system is mostly used in the disinfecting system due to the short periods that fruits have in contact with water, while the jacuzzi system allows fruits to be submerged in hot water for long periods making it ideal for disinfecting purposes. In the batch

Commodity	Treatment protocol	Target	Reference
Mango	46.1–46.7 °C for 45–65 min	*Anastrepha suspensa*[1]	[37]
	46.1–46.7°C for 54 min	*A. suspensa*	[38]
	46.1°C for 90 min	*Anastrepha ludens*[2], *Anastrepha obliqua*[3]	[39]
	46.1–46.7°C for 60–65 min	*A. obliqua, A. suspensa*	[40]
	46.1–46.7°C for 90 min.	*A. suspensa*	[40]
	46°C for 60 min; 46°C for 90 min; 49°C for 120 min	*A. suspensa*	[41]
	48°C for 7.5–30 min	Quality test	[34]
	48°C for up to 90 minutes	*Bactrocera [Dacus] aquilonis*[4]	[42]
	47°C for up to 2 hr. [core temperature]	Quality control	[43]
	46.1–46.7°C for 20–60 min.	*A. obliqua*	[44]
	50°C for 30 min	Quality control	[45]
	45°C for 75 min	Quality control	[46]
	44°C for 25 min [core temperature]	*A. suspensa*	[47]
	48°C for 60–75 min.	*Bactrocera dorsalis*[5]	[48]
	46.5°C for 90 min through phased hot water	Quality control	[49]
Avocado	41°C for 25–30 min, or 42°C for 25 min after cold treatment	Fruit flies	[50]
	38 °C for 1 hr.; 50°C for 1-10 min [pretreatment]	Quality control	[51]
	38 °C for 60 min [pretreatment]	Quality control	[52]
	38 °C for up to 120 min pretreatment for 50°C for 10 min	Quality control	[52]
Bell pepper	45°C for 15 min, 53°C for 4 min	Fungus	[53]
	53°C for 4 min	Quality control	[54]
	55± 1°C for 12 ± 2 s.	Fungus	[55]
	40, 50, 60°C for 2 mins	Fungus	[56]
	53°C, 1 to 3 mins	Quality control	[57]
	55°C for 15 sec	Quality control	[58]

1–5 Are fruit flies [Diptera: Tephritidae].[1]*The Caribbean fruit fly: A quarantine pest of various fruits including mango, citrus, guava, Annona.*
[2]*The Mexican fruit fly: invasive pest, polyphagous attacking mango and citrus among other host plants.*
[3]*West Indian fruit fly: Invasive pest attacking a wide range of fruits among them mango.*
[4]*Very destructive fruit fly with a very broad host range.*
[5]*Oriental fruit fly-devastating invasive fruit fly first reported in Africa in 2003, attacks a wide range of fruits and vegetables.*

Table 1.
Some immersion hot water treatment protocols for disinfesting and disinfecting mango, bell pepper, and avocado developed worldwide.

system, fruits are lowered into large tanks containing circulating hot water either manually or by hydraulics. They have only removed the same way when treatment duration has been completed. On the other hand, the drainage system uses hot water which wets fruits from above as they move on a stainless steel conveyor belt [66]. This is also ideal for disinfecting fruits and vegetables. Due to the large volumes of treated fruit required at commercial scale [in both treatments for disinfecting or disinfesting], the jacuzzi system is slow hence the preference for the CFS which is automated. An ideal HWT treatment equipment must be equipped with a heating mechanism that supplies continuous uniform heat, temperature sensors for temperature regulation, uniform circulation of heated water.

Hot water treatment of fruits is largely dependent on the variety, shape, size and, physiological maturity of fruits. This makes it a garbage in, garbage out (GIGO) process. We strongly opine that most quality challenges in treated commodities emanate from poor selection and handling during harvesting, treatment, and post-treatment. The desire to have fruits last long periods during transit often forces fruit growers to harvest physiologically immature mangoes, which however fail to tolerate heat leading to affected esthetics and physiological internal quality.

2.3 Protocols for HWT developed in Africa

Various protocols particularly for disinfecting and disinfesting mangoes, bell pepper, and avocadoes have been developed in Africa (**Table 2**) but their applicability in real commercial entities is restricted due to various reasons ranging from effects on quality, ease of application, set up cost, and commitment from relevant sectors. Between 2014 and 2019, approximately 29 million tonnes of mango were produced by the top five counties in Africa (**Table 3**), and most of this produce was consumed locally or found its way to less stringent markets such as the Middle East, which are sadly less lucrative.

No commercial HWT facilities are established except for miniature systems used for experimentation in the top twenty producers of mango making it difficult to export to the USA or EU without risking costly interceptions. There are reports

Commodity	Treatment protocol	Target	Reference
Mango	46.1 °C for 81.47 min [95% CL 75.77–87.18 min], with 68 mins equally effective	*Bactrocera dorsalis*	[19]
	46.1°C for 86.7 min [95% CL 77.830–99.880 min] with	*B. dorsalis*	[20]
	52°C for 5 minutes	anthracnose	[67]
	Fruit core temperature of 46.5°C	*B. dorsalis*	[68]
Avocado	38°C for 15–30 min	pathogens and external chilling injury	[69]
	46°C for 5 min	Quality control	[70]
	40°-42°C for 20–30 minutes.	Quality control	[71]
	38 °C for 30 minutes, 42°C for 25 minutes and 46°C for 20 minutes	Quality control	[72]
	38 °C for 5 minutes,	Quality control	[73]
Bell pepper	50°C for 3 min plus Controlled atmosphere packaging	Quality control	[74]
French bean	50 °C for at least 5 min	*Frankliniella occidentalis**	[75]

**Frankliniella occidentalis: Commonly called the Western Flower Thrips, highly polyphagous and invasive [it is a quarantine pest]. Due to insecticide resistance, it is difficult to control through preharvest management options, hence post-harvest through HWT is very effective.*

Table 2.
Some protocols for disinfecting, disinfesting, and enhancing the quality of mango, avocado French bean, and bell pepper in Africa.

County	Mango production [metric tonnes][‡]	Country	Avocado production [metric tonnes][†]
Malawi	8,985,332	Kenya	1,347,713
Nigeria	5,522,388	South Africa	562,589
Sudan	4,962,904	Malawi	557,444
Kenya	4,777,695	Cameroon	444,066
Mali	4,400,374	DRC	360,374
Tanzania	2,215,309	Ethiopia	339,854
Madagascar	1,483,336	Côte d'Ivoire	185,628
DRC	1,242,251	Madagascar	158,828
Niger	1,065,111	Eswatini	56,979
Guinea	1,064,577	Ghana	54,665
Senegal	781,636	Congo	48,411
South Africa	544,177	Rwanda	47,847
Ethiopia	510,148	CAR	44,624
Ghana	509,639	Zimbabwe	15,532
Côte d'Ivoire	471,680	Zambia	3,941
Uganda	451,357	Réunion	3,531
Congo	182,075	Eritrea	954
Mozambique	175,803	Seychelles	65
Chad	174,792		
Sierra Leone	143,996		

[‡]*High production of mango.*
[†]*Avocado which could be exported to lucrative export markets if hot water treatment facilities were readily available. DRC: Democratic Republic of Congo; Congo: Congo Brazzaville; CAR: Central African republic.*

Table 3.
Top twenty producers of mango and avocado in Africa between 2014 and 2019 [76].

that Mozambique subjects its mangoes for export to South Africa, to HWT at 47°C for 12 minutes, [77] but it is unlikely that this treatment is adequate to disinfest any fruit fly or insect pest of mango. It has been demonstrated that at 46.1°C for durations less than 68 minutes, *B. dorsalis* larvae can still survive in apple mango variety weighing up to 500 g [19]. The most thermotolerant stage of development of this pest was only killed by continuous exposure to hot water treatment for a minimum of 68 minutes.

2.4 HWT protocols for mango

Malawi, Nigeria, Sudan, Kenya, Mali, Tanzania lead in mango production and all are struggling to satisfy requirements for the USA and EU market. Systems approach centering on preharvest management of pests often fails due to the nature of production in Africa. The systems approach works best when area-wide-IPM is practiced. Sudan does not use immersion HWT but has been exporting mangoes subjected to Vapor Heat Treatment (VHT) [78] for the past eight years now. The Sudanese Center for Sterilization of Horticultural Exports [SCS] was established in 2013 specifically to offer VHT services to the horticulture sector. The Centre is unique in that it is the first institution in Africa and the Middle East to offer such services. Mangoes are subjected to 95% Relative Humidity (RH) to achieve pulp temperature of 46–48°C for 30 minutes.

Hot Water Treatment experiments conducted in Ghana on the Keitt mango cultivar at 52°C for 5 minutes was effective in controlling anthracnose for 21 days in storage [67]. The treatment did not affect total soluble solids, titratable acidity, pH, and firmness thus was deemed adequate for adoption by the private sector. However, only 70 mangoes were used in the trial, and the equipment used was not mentioned. This has been the problem with some protocols because temperature regulation and water circulation are key yet they are not mentioned in the experimental design.

Similar experiments were also conducted in Benin on Kent cultivar at various temperature and duration regimes, but the authors recommended a treatment that results in a core temperature of 46.5°C as the most effective to provide quarantine security against *B. dorsalis* in export mango [68]. They also proposed a lower temperature between 42.0°C and 46.5°C as being similarly effective and preferable as it would result in reduced energy costs to implementers. Their treatment protocol resulted in some effects on fruit quality, and they proposed pre-conditioning fruits by subjecting them to heat before treatment and, hydro cooling the fruits after treatment to ameliorate quality challenges.

Further trials were conducted in Kenya on Apple mango at a temperature of 46.1°C for 81.47min with 95% confidence limits set at 75.77–87.18 min [19]. However, efficacy data consistently showed that 68 mins were equally effective in disinfesting mangoes of up to 500 g against the devastating *B. dorsalis*. This work also reported thermal tolerances for the various stages of development viz. eggs, first, second and third instars, with the third instars being the most heat tolerant stage of development. The protocol has since been submitted to the EU by the Kenya Plant Health Inspectorate Service (KEPHIS), the National Plant Protection Organization responsible for the regulation in Kenya, and duly recognized as an effective treatment. A pilot mango consignment treated at 46.1°C for 68 min was shipped to Italy in July 2021 by a renowned exporter Fresco Freshpro Limited and passed all phytosanitary requirements as well as quality concerns with consumers.

Recently, another protocol was developed for the disinfestation of *B. dorsalis* in Tommy Atkins mango cultivar in Uganda [20]. The temperature was set at 46.1°C and mangoes used weighed between 500 and 700 g. The ideal treatment duration was determined at 86.7min with 95% confidence limits at 77.830–99.880 min. The most heat tolerant stage was the third instar and the egg was the least tolerant just as in the study conducted on apple mango in Kenya.

These protocols provide an ideal alternative to postharvest treatments and may be adopted by countries wishing to use HWT for disinfestation and disinfection.

2.5 HWT protocols for avocado

Kenya and South Africa lead in the production of avocado (**Table 3**), however cold treatment in transit (commercial shipping temperature of approx. 5.5°C for up to 28 days) is mostly used or in some instances, the fruits are ripened, peeled, and frozen before export. Most South African Avocadoes are exported to Europe under the SADC/EU Economic Partnership Agreement and the Southern African country is making efforts to secure markets in the USA, India, Japan, and China [79]. Though cold treatment in transit offers adequate phytosanitary assurance against quarantine pests, it affects the quality of the fruits through chilling injury [71]. Several investigations have been conducted to ameliorate cold injury through the use of various treatments which include short exposures to HWT. However, there are many views regarding the efficacy and applicability of HWT in avocado [69] and trials are still being conducted to date [72].

At the peak of the *B. dorsalis* incursion in Africa, experiments were conducted to determine a cold treatment protocol to disinfest avocado from the devastating quarantine pest. Results indicated that a temperature of 1.5°C or lower, applied continuously for 18 days was adequate to kill all stages of development of *B. dorsalis* and offer phytosanitary security against the risk of introducing the pest in new territories [18]. Though these findings were in agreement with similar protocols requiring avocado to be subjected to temperatures of 1°C for 20 days [80] or 1.1–2.2°C for 14–18 days as was prescribed by USDA then, issues of fruit quality due to chilling injury remained unaddressed. Attempts to validate the 1.5°C for 18 days protocol at the Horticultural Crops Directorate (HCD) center in Kenya yielded mixed results as fruits were damaged by cold injury. Opinion has it that avocadoes must not be subjected to temperatures lower than 5°C or greater than 10°C after harvest [81]. However, this could be a major challenge considering the production system in Africa outside South Africa, where temperature-controlled systems are poorly developed. The commercial shipping temperature in South Africa is 5.5°C for 28 days, thus it could be possible that temperatures lower than this threshold may be detrimental to avocado quality.

Several studies in South Africa, have confirmed that HWT for shorter periods may confer some tolerance to cold and result in less injury than what is currently experienced and additionally disinfect the fruits against major pathogens (**Table 2**). For example, a 40°-42°C for 20–30 minutes HWT regime was found adequate to reduce chilling injury but specific protocols were required for each variety and also tested at various levels of maturity [71]. Inconsistencies in findings have largely contributed to a reluctance to adopt some protocols. For example, HWT at 46°C for 5 min produced inconsistent results in two tested varieties namely Hass and Fuerte [70]. The same treatment had given promising results in Australia, with positive physical appearance qualities after treatment and storage at 1°C for 16 days. The treatment also adequately disinfested the fruits from the Queensland fruit fly *Bactrocera tryoni* [82].

Experiments conducted at 38°C for 15–30 min yielded inconclusive results and still required further tests though the regime reduced the severity and occurrence of pathogens, and also cold injury [69]. Hot water treatment at 38°C for 5 minutes also promises to deliver the required quality but only when accompanied by waxing, special packaging using low-density polyethylene, and stepping down storage temperature from the conventional 5.5°C to 4.5°C [73]. The chilling injury was reduced and uniform ripening improved when HWT was conducted at 38°C for 30 minutes, 42°C for 25 minutes, and 46°C for 20 minutes [72]. The treatments outlined above require harmonization and validation for specific varieties at various levels of maturity. This will enable a holistic approach to the attainment of export quality through both disinfection and disinfestation. Avocadoes are susceptible to pathogens and pests like the false codling moth. They are bulky thus cannot be exported by air due to the cost connotations thus export by sea is the most feasible and cost-effective way. A sharp balance that guarantees freedom from pathogens and insects at the same time ensuring that avocadoes reach their destination without physical damage and deterioration in esthetic value must be struck if Africa is to compete at the world stage. This looks possible if correct HWT parameters are established, validated, and adopted.

2.6 HWT protocols for bell pepper

Not so many references are available in the literature for either disinfection of pathogens or disinfestation of insects in bell pepper in Africa most probably due to its susceptibility to heat and poor equipment to conduct such delicate work. At the world stage a couple of references are available notably on enhancing quality before cold treatment or disinfection [51–57]. In the African context, bell pepper was subjected to HWT at 50°C for 3 min before being stored in controlled atmosphere packaging [74]. This was adequate to kill pathogens, slow down weight loss, and loss of carotenoids and ascorbic acid.

More research is being conducted in Kenya to develop protocols for providing phytosanitary security against the devastating native invasive pest the false codling moth *T. leucotreta.* Results are promising and the private sector is eagerly waiting (Mwando et al. unpublished data a).

2.7 HWT protocols for French beans

French beans are mostly exported fresh and the western flower thrips *F. occidentalis* pose a great risk of being transported to new areas where they could potentially cause huge damage. This is so because the pest has developed resistance to major classes of insecticides thus preharvest management techniques alone are inadequate [83]. The pest poses a double not only causes direct damage but also vectors deadly viruses which are a huge threat to the horticulture industry [84]. A pilot trial to disinfest French beans using HWT was conducted at 50°C for 5 min and was found effective in causing 100% mortality of thrips eggs. The treatment did not affect the quality of French beans. Further validation has been conducted to establish a feasible protocol that can be adopted by the private sector (Mwando et al. unpublished data b).

3. Challenges affecting hot water treatment technology

Though various protocols have been developed in Africa and elsewhere, adoption by the private sector has been slow and absent in many parts of Africa. Protocols have remained on shelves unused. Most of these protocols have been developed used using water baths using very small sample sizes which can hardly be extrapolated to commercial scales. In some cases, the studies are silent on the equipment used and how heating, water circulation, and temperature regulation were achieved yet these are vital components of any HWT system. The stage of maturity of fruits is another factor that largely affects the quality of treated fruits. Most often, immature fruits are harvested by growers in a bid to ensure that they stay longer on the shelf. Maturity indices are also lacking and growers rely on visual characteristics which are not always accurate. The aspect of maturity is bound to be the sticking point because avocadoes and mangoes are bulky and are likely to be exported by sea to reduce transport costs, thus fruits are bound to be harvested earlier before reaching full physiological maturity to withstand the long voyage to Europe, America, India or China.

Resources are a limiting factor in adopting HWT in Africa with various small to medium scale enterprises unable to gather adequate startup capital. However, in our experience, we have noticed that some private sector partners have misplaced expectations, and require out-of-this-world automated facilities yet the HWT itself is simple and affordable. We opine that it is far much cheaper and easier to run and maintain than a VHT facility of similar size and capacity. Hot water treatment protocols for disinfecting fruits and vegetables usually prescribe a longer treatment duration which may be put off to potential users. The insistence of probit 9 as the required quarantine efficacy level frequently overestimates treatment times. This can be evaded by adopting other statistical analyses which equally show how effective a treatment is.

The emergence of less stringent markets in the Middle East has also provided local fruit growers and exporters with alternative markets where they send their products with less hustle. Thus investing in HWT equipment is seen as an expensive venture.

The lack of holistic protocols validated at a large scale has also been another impediment. There is a need to validate the most promising protocols and seek buy-in from major industry players if HWT is to be fully adopted at a commercial scale. Poor circulation of water and regulation of temperature also impact the quality of fruit. Hot water treatment requires a sizeable investment into good probes, data loggers, and automated controls. Too much fluctuation of temperature during treatment can be detrimental to the final product. Combination treatments are poorly developed or are simply expensive to implement. In cases where HWT cannot be a stand-alone treatment due to the susceptibility of the commodity to heat, combination treatments may then be used to circumvent the challenge. If there is a mismatch in heat tolerance between the commodity and pest, for example in instances where the pest is tolerant to higher levels of heat which cannot be tolerated by the fruit or vegetable, then HWT will not be feasible [85]. Thus the above suggestion may work.

4. Benefits of HWT

The biggest benefit of HWT is that it has a triple function of cleaning, disinfecting [86], and disinfesting [19, 20, 37]. During the treatment process, dirt, debris, and any extraneous material are removed which could potentially affect fruit or vegetable quality. Most systems incorporate a hot water brushing and rinsing station where fruits are scrubbed and rinsed dry by cool air [87]. This stage is absent for example in VHT and fungicides are easily applied if need be at this stage. The technology is relatively uncomplicated, uses clean water from conventional water sources, and is purely a non-chemical postharvest disinfestation process [88]. The cost of setting up a HWT facility is considered far much less (10%) than setting a similar VHT facility [89]. Treatment by VHT often causes scalding if vapor is not uniformly distributed, while a simple water pump can easily distribute heat uniformly in immersion HWT. Compared to irradiation and chemical treatments, HWT does not use chemicals, hence leaves no residues on treated commodities ([88] and references thein). When chemicals are used in the disinfestation of fruits e.g. the use of methyl bromide fumigation, residues are left on the fruits which pose health risks to consumers. Consumerism is increasing all over the world and consumers are becoming aware of their rights and continuously demand to be served healthy food.

Hot water treatment slows down ripening in fruits thus increasing shelf life [90]. Shelf life is very important as fruits and vegetables are perishable [74]. From harvest to consumption there is a huge lag that requires that fruits be kept in good quality to enable transportation and storage before reaching consumer tables. Experiments have also shown that HWT can confer tolerance of low temperature (chilling injury) in some fruits such as avocado [72]. Short treatments of fruits before cold treatment have been shown to reduce injury caused by excessive cold. Subjecting fruits to HWT before the actual treatment (particularly cold) is becoming more applicable because of the positive benefits.

5. Prospects

Hot water treatment may be the future of sustainable postharvest treatment of fruits and vegetables in Africa. Thus more investment into precision equipment is required. Equipment with state-of-the-art sensors, heating, and circulation apparatus. This will ensure that research is conducted in commercial facilities allowing large-scale validations to be performed. Many deformities, injuries, and effects on sensory parameters are results of poor equipment being used. Research at the molecular level is required to determine heat regimes that are not detrimental to finer qualities at the micro and macro protein levels. Combination treatments must be explored especially for heat susceptible fruits and vegetables. The combination treatments must be relatively affordable. With the wider acceptance of insects for food, the use of chitin in coating to increase shelf life must be explored [91].

It is imperative to develop specific protocols that consider variety, size, maturity, and other factors than use blanket treatments that produce horrible results. This may be costly initially but very profitable in the long run. Standards will eventually have to be developed, so that uniformity in operations is maintained. The whole system requires a Multi-stakeholder approach than lone attempts in such a global village. In such a case, customization and harmonization of protocols become feasible resulting in cost-saving especially in instances where fruit varieties/cultivars are similar and there are no significant differences in size and other physical and physiological characteristics.

6. Conclusions

Hot water treatment is the future of postharvest treatment of fruits and vegetables in Africa. Africa is a potential giant to feed the world with fruits and vegetables considering the favorable climatic conditions favoring production. However, the huge threat posed by devastating invasive pests hinders Africa from exporting to lucrative exports markets such as the USA and Europe. Several protocols have been developed for disinfestation and disinfection of commodities by their adoption far lags. Besides providing phytosanitary security, HWT can also enhance fruit quality by activating polyamines and heat shock proteins that enrich fruit and vegetable shelf life. Africa is indeed on the rise, to implement HWT technology and export large volumes of fruits and vegetables thereby increasing her foreign currency earnings.

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Conflict of interest

The authors declare no conflict of interest.

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Author details

Shepard Ndlela*, Nelson L. Mwando and Samira A. Mohamed
International Centre of Insect Physiology and Ecology, Nairobi, Kenya

*Address all correspondence to: sndlela@icipe.org; shepardndlela@gmail.com

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