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Quantification of On-Farm Pomegranate Fruit Postharvest Losses and Waste, and Implications on Sustainability Indicators: South African Case Study

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Abstract: While there is a growing body of scientific knowledge on improved techniques and procedures for the production and handling of quality pomegranate fruit to meet market demand, little is known about the magnitude of losses that occur at the farm and post-farmgate. This study revealed the amount of pomegranate fruit lost on the farm and the causes of loss and estimated the impacts of losses. The direct measurement method, which involved sorting and counting of individual fruit, was used since physical identification of the causes of fruit losses on individual fruit was necessary for data collection. Furthermore, qualitative data were collected by physical observation during harvesting and interaction with farm workers. At the case study farm in Wellington, Western Cape Province of South Africa, a range of 15.3–20.1% of the harvested crop was considered lost, as the quality fell below marketable standards for retail sales. This amounted to an average of 117.76 tonnes of pomegranate fruit harvested per harvest season in the case study farm, which is removed from the value chain and sold mainly at a low value for juicing and other purposes and translates to an estimated R10.5 million ($618,715.34) economic loss to the farmer. Environmental factors are the main causes of on-farm fruit losses. In the three pomegranate cultivars studied, sunburn and crack were identified as the leading cause of fruit loss, accounting for about 43.9% of all on-farm fruit losses. The lost fiber, carbohydrate, protein, iron and ascorbic acid contents associated with lost fruit were estimated to meet the daily recommended nutrition intake of 2, 9, 4, 2 and 24 people, respectively. Strategies to control and reduce pomegranate fruit losses and waste at the farm level should focus on environmental factors and mechanical damage since they account for the highest sources of fruit losses. This will ensure improved revenue to farmers, sustainable use of natural resources, reduction of the environmental impacts of the fruit industry, and more availability of quality fruit for nutritional security.

Keywords: pomegranate; losses; nutrition; environmental; resources; unsustainable; impacts

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1. Introduction

The importance of the consumption of fruit and vegetables as part of the human daily diet has been stressed by the World Health Organization (WHO). The recommendation of the WHO is to consume at least 400 g/capita/day of fruit and vegetables to provide adequate and essential nutrients to the human body [1]. Consumption of fruit and vegetables is known to provide multiple nutrients compared to biofortified foods and supplements that are manufactured [2]. The importance of fruit and vegetable consumption is numerous and is evident in their ability to help reduce susceptibility to diseases such as cancer, cardiovascular diseases, high blood pressure, diabetes and other chronic diseases [3]. These diseases contribute to the high rate of mortality, especially in developing countries, and impose a huge cost to the health care system in these countries [4].

Malnutrition is a major health-related problem the world is facing, among other challenges. Malnutrition-related problems such as micronutrient deficiency, undernutrition and excessive consumption of fat and foods high in carbohydrates affect not less than a third of the world population and impact negatively on the quality of life [2]. Furthermore, the prevalence of diseases due to malnutrition has a direct impact on attaining some of the Sustainable Development Goals (SDGs) [4]. For healthy living, a balanced diet is necessary and can be achieved by the consumption of an appropriate amount of nutrients such as vitamins, amino acids, minerals, calories and fiber [2,3]. Fruit and vegetables contain these nutrients that are necessary for healthy living in diverse quantities [4,5].

Fruit and vegetables are prone to a high incidence of postharvest losses and waste, largely in part due to their high moisture content (often exceeding 80%), high respiration rate and susceptibility to handling damage. The high incidence of fruit and vegetable postharvest losses has remained a major challenge to food and nutritional security [6,7]. Global estimates on the amount of postharvest losses of fruit and vegetables range from 37 to 55% [8], and this is the highest among all food commodities, with an estimated economic loss of $750 billion per annum [9]. In South Africa, fruit and vegetable losses are estimated at 4.2 million tonnes, accounting for 47% of the total food losses and waste in the country [10]. A high level of postharvest losses and waste, especially in developing countries, has prompted consensus among food system experts that reducing postharvest losses is one of the strategies to increase food and nutrition security amid the increasing world population [7]. Hence, reducing postharvest wastage of fruit and vegetables could be one of the ways to reach many of the SDGs such as Goal 2 (Zero Hunger), Goal 3 (Good Health and Well-being), Goal 12.3 (Halve per capita global food waste by 2030) and Goal 13 (Climate Action).

Postharvest loss in the context of this study refers to fruit with reduced quality due to defects, leading to downgrading and consequently economic loss, which are usually sold at cheap price for fresh consumption or used for industrial purposes. What this means is that the farmer loses return on investment as fruit are not sold at an optimum price due to quality defects. This definition may be different from that of some researchers, as the definition of postharvest loss is context-dependent.

Status of Pomegranate Fruit Production and Losses in South Africa

Production and consumption of pomegranate have grown globally, with more than 500 different cultivars grown in different parts of the world [11]. Global production was estimated to have increased from about 3 million tonnes in 2014 to 3.8 million tonnes in 2017 [12]. Despite the increase in production and technological innovations in packaging and postharvest handling [13–17], the incidence of postharvest losses and waste persists [12,18]. This is because pomegranate fruit is highly susceptible to losses and waste due to several preharvest and postharvest factors such as diseases attack [19], bruise damage [14], high rates of transpiration and respiration of fruit resulting in weight loss and quality loss during storage [17,20,21].

During the past decade, there has been a marked increase in the total area of land used for the cultivation of the various cultivars of pomegranate fruit in South Africa. This is evidenced by the significant increase from below 800 ha in 2011 to about 1024 ha in 2019 [18]. The total export has also increased rapidly. In 2019, about 76% of the total production was exported to the United Kingdom, Russia, Asia and the Middle East [18]. This resulted in an increase from 483,609 cartons (3.8 kg equivalent per carton) in 2012 to 1,676,160 cartons in 2019 and is projected to increase to 2,055,271 cartons by 2024 [18]. Increased production and export has established South Africa as an important producer in the Southern hemisphere, which enables it to fill the niche market gap in the Northern Hemisphere due to different seasons of production in the two regions [18,22].

In South Africa, the incidence of pomegranate fruit losses in the industry are historically measured only at the packhouse level, and this presents a problem in proffering solutions to be tailored to the farm level. Losses have been reported with variation in the three most grown cultivars in the country from 2016 to 2019 (Table 1). Between 2016 and 2019, 'Hershkawitz' accounted for the highest annual incidence of postharvest losses at the packhouse with a mean value of 15% of loss, followed by 'Acco', with a mean value of 8.8% loss and lastly 'Wonderful' with a mean value of 7% loss (Table 1).

Table 1. Annual and mean incidence of losses (%) of pomegranate fruit at the packhouse level for the three major pomegranate cultivars in South Africa (From 2016 to 2019).

Year	Wonderful	Hershkawitz	Acco	Reference *
2016	1.0	14.0	2.0	[23]
2017	11.0	13.0	11.0	[24]
2018	7.0	8.0	9.0	[25]
2019	9.0	25.0	13.0	[18]
Mean	7.0	15.0	8.8	

* Pomegranate Producers Association of South Africa.

While there is a growing body of scientific knowledge on improved techniques and procedures for the production and handling of quality pomegranate fruit to meet market demand, little is known about the magnitude of losses that occur at the farm and post-farmgate. This information is needed to guide the development and application of an evidence-based scientific solution to reduce fruit wastage in specific value chains. Typically, in South Africa, pomegranate fruit is harvested and sorted on-farm while the tractor moves along the farm rows until the bins are full and moved to the farm shed where records of the harvest are taken. The bins are then transported to the packhouse immediately for sorting and grading before transportation to cold storage. Fruit losses may occur at each of these steps. This study aims to quantify the magnitude, identify causes and estimate the environmental impacts of on-farm pomegranate losses at the case study farm in South Africa.

Generally, only a few studies on on-farm quantification of food losses and waste have been published [26,27]. This means that on-farm losses and waste measurement is not often done or has not been recorded [28]. The lack of quantitative data at farm level may be a result of the cost and time, given that direct on-site measurements are usually expensive and time-consuming [28,29]. Other factors are lack of cooperation from farmers, production variability and concerns about food safety, which limit access to farms [30].

2. Materials and Methods

2.1. Research Design

The study was done by assessing fruit bins harvested on the farm each day. The assessment started at about 8:00 a.m. and ended by 4:00 p.m. daily. The study was carried out in February and March. 'Herskawitz', which is the early cultivar, was assessed by mid-February, 'Acco' was assessed by late February and early March, and 'Wonderful', the late cultivar, was assessed by late March before the COVID-19 pandemic national lockdown in South Africa. Harvesting and handling practices at the farm were observed. The unit of measurement used is the fruit bin with the following dimensions: length = 1270 mm × width = 1070 mm × height = 720 mm. A total of 18 bins for all the three cultivars were studied, six bins for each cultivar. Loss calculations included fruit discarded in the 'waste bin' for defect reasons but did not include fruit left in the field, which was insignificant in number. The trees were harvested up to three times with different harvesting rings to ensure that a particular size of fruit was harvested each time. This means that trees were almost completely stripped by the last harvest and hence the amount of fruit left in the field was insignificant. The assessment was done by the same person based on the external quality of fruit. Quantification was done by sorting and counting of fruit to identify reasons for the loss and how they contribute to total fruit loss.

2.2. Research Method

Different approaches have been used by researchers to conduct postharvest wastage studies, which include sampling [31,32], surveys [31,33–35] and estimates [36]. Since this study involved the physical identification of the causes of fruit losses and waste on individual fruit, sorting and counting was the preferred method for data collection. Furthermore, qualitative data were collected by physical observation during harvesting and interaction with the permanent farm workers.

The data collection protocol is consistent with the direct measurement method of the Food Loss and Waste Protocol (FLWP) [37] as the reporting includes factors considered in the Food Loss and Waste Accounting Reporting Standard [37]. The factors include the material type, the intended market, the life cycle, time of data collection and the final destination of losses. The material type was the pomegranate fruit. The intended market is mostly the export market in the United Kingdom, Russia, the Middle East and Asia [18]. Since pomegranate trees produce fruit over several years, their life cycle falls within the perennial crops. Data for this study were collected in February and March 2020 in the Western Cape Province of South Africa, and the fruits reported as lost were sold at a cheap price for juicing and animal feed. On-farm loss assessment involved direct measurement by monitoring tractors carrying bins of harvested fruit along the farm rows and to the farm shed, where the ‘waste bins’ were sorted and the individual pieces of fruit were counted in portions according to the defects observed on the fruit [37,38].

The economic impact of pomegranate losses and waste was estimated using the supermarket retail price (ZAR89.99/kg) in Stellenbosch, Western Cape, South Africa. The environmental impacts were estimated using the values from previous studies. The energy used and GHG emission values were estimated using 6.1 MJ/kg and 0.48 CO_2 eq/kg, respectively [39]. The water footprint was estimated as 910 m^3 ton^{-1} [40]. The nutritional impacts were estimated using values from Spiker et al. [41] and Paul and Shaha [3]. Lastly, cropland use was estimated by the size of the farm and the average yield produced.

2.3. Data Collection

Data collection involved monitoring bins of fruit conveyed by tractors. For each cultivar, six tractors, each conveying six fruit bins, were monitored during harvesting as they moved along the farm rows until the bins were full and unloaded at the farm shed, where sorting, counting and recording was done. Fruits were assessed by physical inspection and categorized by the following factors: *Alternaria*, oversize, bruise, sunburn, crack, insect damage, crown rot, decay, blemishes and undersized/misshapen (Figure 1). Each of these factors is discussed in detail in Section 3.2.

Data collection for each cultivar was done in three days, and 6 bins (n = 6) were assessed per cultivar (Acco, Hershkawitz and Wonderful). Bins 1 and 2 were assessed on day one of assessment, bins 3 and 4 assessed on day 2 and bins 5 and 6 were assessed on day 3. The tractors conveying the fruit bins were also marked, and 6 tractors (n = 6) for each cultivar were used. The fruit was harvested with plastic rings (fitted on fruit to measure the size of the fruit) to ensure that particular sizes of fruit were harvested on each day, except for ‘Wonderful’, where the trees were completely stripped at once (harvested without ring measurement) due to imminent lockdown during the onset of COVID-19 pandemic.

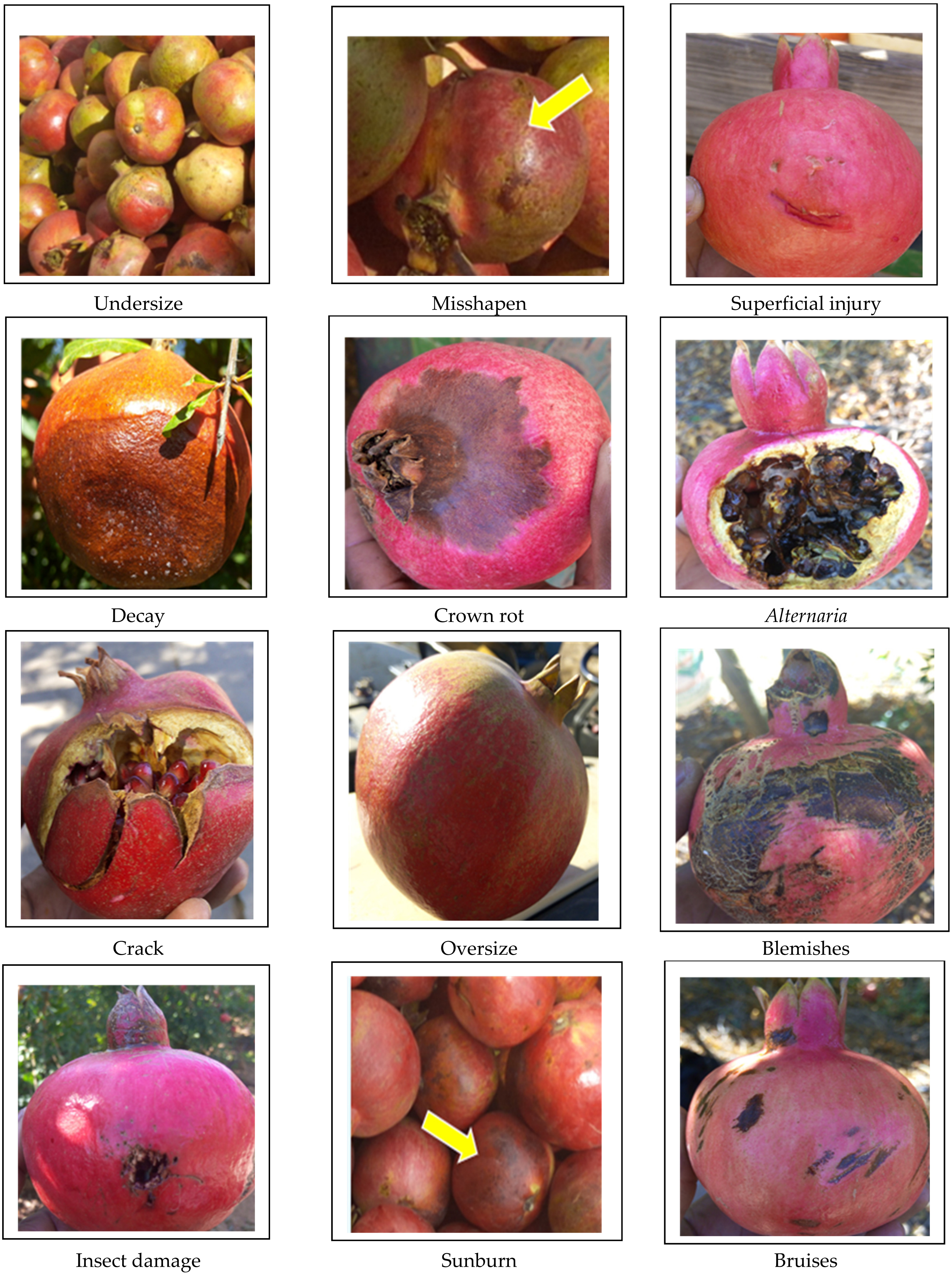

Figure 1. Photographs of fruit showing defects.

2.4. Statistical Analysis

Microsoft Excel 2013 (Microsoft Corporation) was used to collate the data recorded on the farm. Mean value ± standard error of fruit defects were presented. Analysis of Variance (ANOVA) was performed using Statistica Version 13.5.0 to evaluate differences between cultivars and fruit defects. Where there was a statistical significance difference ($p < 0.05$), differences between means were separated using Duncan's multiple range test. To find the trend of variation between cultivars and fruit defects and to consider their correlation, data were investigated according to principal component analysis (PCA) using XLSTAT software Version 2012.4.01 (Addinsoft, France).

3. Results

3.1. Magnitude of Fruit Losses and Waste

The magnitude of fruit losses for 'Acco'and 'Hershkawitz' was similar, given that for every five bins of 'good fruit', one bin of 'lost fruit' was produced. For 'Wonderful', it was observed that for every four bins of 'good fruit', one bin of 'lost fruit' was produced. Loss quantification involved a total of 96 bins of harvested fruit from three cultivars, of which 18 bins were sorted out as 'lost fruit' and removed from the value chain. The total lost fruit (often referred to as 'discarded' in industry) ranged from 15.3 to 20.1% of the harvested fruit among the three cultivars studied (Table 2). 'Acco' and 'Hershkawitz' showed a close range in the quantity of fruit discarded. About 15.8 to 16.5% of the harvested 'Acco' fruit were discarded, and 15.3 to 16.2% of the harvested 'Hershkawitz' was discarded. The similarity in magnitude of fruit loss could be attributed to the fact that both cultivars were harvested in due time and with the harvesting rings to ensure that the right sizes of fruit were harvested.

Table 2. Quantity (number) and percentage (%) of lost (discarded) fruit after harvest in the three pomegranate cultivars at the case study farm.

Cultivar	Good Fruit	Discarded Fruit	Discarded Fruit (%)
	Min–Max	Min–Max	Min–Max
Acco	7274–7330	1370–1432	15.8–16.5
Hershkawitz	7296–7373	1327–1404	15.3–16.2
Wonderful	5793–5825	1425–1457	19.7–20.1

'Wonderful' cultivar showed a difference from 'Acco' and 'Hershkawitz' in the range of the quantity of fruit discarded. The discarded fruit ranged from 19.7 to 20.1% of the harvested 'Wonderful' fruit. 'Wonderful' is a late cultivar with big fruit of larger surface area and as a result becomes more susceptible to damage due to environmental factors such as high temperature in the summer that causes sunburn. Although 'Wonderful' was harvested in due time, it was harvested without the harvesting rings. The trees were stripped at once, including the undersize and misshapen fruit. This is because the farmer anticipated the national lockdown due to COVID-19 pandemic that was implemented by the South African government by late March 2020. The decision to strip the trees at once was economical and morphological as well. According to the farmer, it was better to harvest as much fruit as possible and send to the packhouse for processing since the conditions of the anticipated national lockdown were unknown at the time. Again, the farmer stated that for morphological reasons, it was better to strip the trees instead of leaving the fruit to rot and decay on the trees. This is in order to avoid unnecessary stress on the trees and potential pest and disease attack due to rotten and decayed fruit hanging on them.

Many studies have been conducted to estimate the postharvest losses of many fruit, but there is a lack of information about pomegranate fruit losses, especially at the farm (orchard) level. The total pomegranate fruit loss in this study ranges from 15.3 to 20.1% of the harvested fruit. Sudharshan and Anand [42] reported a 6% loss of pomegranate fruit at farm level in Bangalore and 8% loss of pomegranate fruit in Mangalore, both in India. The report of lower losses could be attributed to pre-harvest activities and environmental factors. Furthermore, the method of data collection used in the study is the structured interview to get estimates from farmers. However, Baker et al. [30] suggest that farmer estimates may be inconsistent with actual losses and waste at the farm, citing difficulty with farmers estimating their losses and waste.

A 6.81% of postharvest losses of banana at farm level was reported by Jadhav et al. [43]. The multi-stage stratified random sampling approach was used for the estimation. The study revealed that the causes of loss are similar to this present study as factors such as mechanical damage and poor handling method contributed to significant losses. Springael et al. [44] reported a postharvest loss of 10 to 25% of fruit during transportation of apple in Belgium. The quantification was done by vibration measurement experiment. The study established vibration (mechanical damage) as a major source of loss, causing bruises and punctures on the apples that later led to fungi disease infection through the broken tissues. The effect of bruise on banana and apple is the same on pomegranate due to its high moisture content. These studies showed a similarity to this present study in the causes of fruit loss. The variation in the magnitude of loss could be attributed to the data collection method and physiological attributes of the fruit.

However, the authors consented that postharvest wastage means loss of revenue and unsustainable use of various production inputs and natural resources, which are scarce in supply. Furthermore, there is a huge implication of postharvest losses on food and nutritional security, because essential nutrients which could benefit humans are lost, when not less than a third of the world population suffer from malnutrition [2].

3.2. Causes of Farm Pomegranate Fruit Losses

The causes of pomegranate fruit losses and waste were assessed based on the reasons why fruits were sorted from the supply chain. Such reasons include quality issues caused by environmental factors, mechanical damage and pests and diseases [30]. The two major reasons for the physical loss in pomegranate fruit, as identified in this study are environmental factors such as sunburn and crack. Other reasons for loss include crown rot, *Alternaria*, insect damage, blemishes, decay, injury, undersize and misshapen, oversize and bruise. To establish the relationship between pomegranate fruit defects and how they affect each other, Pearson correlation analysis was used to investigate the interrelationship.

3.2.1. Environmental Stress (Sunburn, Cracks and Splits)

Sunburn

Sunburn was recorded as the most conmon reason for fruit loss in the three pomegranate cultivars assessed. For 'Acco', it accounted for 24.04% of losses, and it accounted for 21.25% of losses in 'Hershkawitz'. It was highest in 'Wonderful' with 28.80% of losses (Figure 2). Sunburn showed a very strong positive correlation with oversize fruit (Table 3), which was mostly observed in 'Wonderful'. Usually, 'Wonderful' produces big-size fruits with a larger surface area that are often exposed to direct sunlight outside the tree canopy. Additionally, 'Wonderful' is a late cultivar, and that means that it is exposed to the sun for a more extended period than 'Acco' and 'Hershkawitz'.

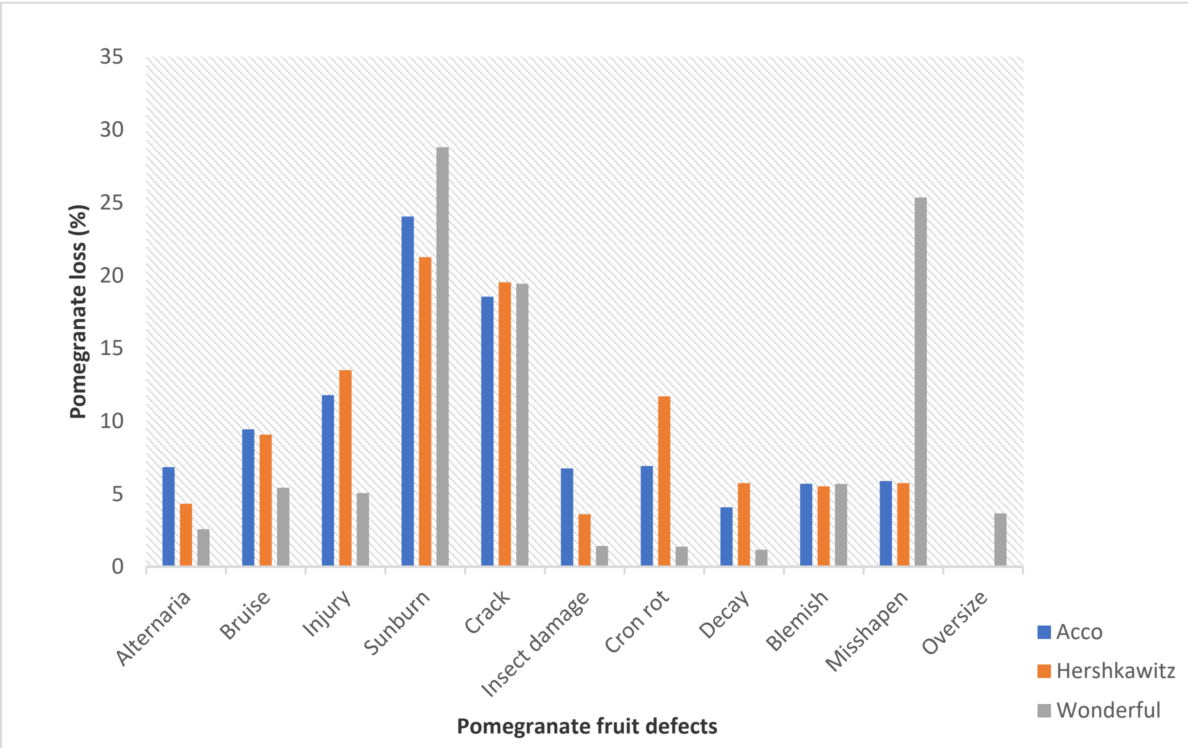

Figure 2. On-farm percentage loss of pomegranate fruit due to defects.

Table 3. Pearson correlation coefficient matrix between defects in 'Acco', 'Hershkawitz' and 'Wonderful'.

Defects	Alternaria	Bruise	Injury	Sunburn	Crack	Insect Damage	Crown Rot	Decay	Blemish	Misshapen	Oversize
Alternaria	**1**										
Bruise	**0.774**	**1**									
Injury	**0.605**	**0.886**	**1**								
Sunburn	−0.456	**−0.760**	**−0.904**	**1**							
Crack	**−0.510**	**−0.553**	**−0.546**	0.453	**1**						
Insect damage	**0.943**	**0.806**	**0.657**	−0.440	**−0.641**	1					
Crown rot	0.397	**0.734**	**0.903**	**−0.968**	**−0.478**	0.409	**1**				
Decay	**0.488**	**0.769**	**0.873**	**−0.953**	**−0.543**	**0.471**	**0.957**	**1**			
Blemish	−0.147	−0.287	−0.263	0.261	−0.064	−0.011	−0.231	−0.207	**1**		
Misshapen	**−0.729**	**−0.913**	**−0.947**	**0.889**	**0.588**	**−0.758**	**−0.888**	**−0.899**	0.138	**1**	
Oversize	**−0.761**	**−0.907**	**−0.909**	**0.889**	**0.556**	**−0.748**	**−0.869**	**−0.907**	0.190	**0.978**	**1**

Values in bold are significant at $p < 0.05$.

Sunburn is as a result of the sun rays hitting the fruit directly, thereby causing discoloration of the fruit rind. The discolouration of the affected fruit reduces the fruit appeal, causing qualitative loss [45,46]. Yazici and Kaynak [47] established that sunburn occurs when fruit surface temperature reaches 35 ± 1 °C. Hence, high temperature mostly exceeding 35 °C as experienced in the Western Cape last summer could be a factor for the high incidence of sunburn. Furthermore, low relative humidity and high air temperature have been identified as contributing to sunburn [47].

Cracks and Splits

The results also show that crack and splits are major sources of pomegranate fruit loss. They were the second-highest cause of loss in 'Acco' and 'Hershkawitz', and the third cause of loss in 'Wonderful'. In 'Hershkawitz' and 'Acoo', they accounted for 19.53% and 18.54% of losses, respectively (Figure 2). For 'Wonderful', 19.43% of loss is attributed to crack and splits. Although crack and splits in pomegranate is mostly attributed to soil moisture content [48–50], the correlation matrix shows that crack and split have a very significant positive relationship with oversize fruit (Table 3), which were observed in 'Wonderful'. This is because oversize fruit loses moisture as they are mostly exposed to the sun and the loss of moisture content stretches the rind of the pomegranate fruit and causes them to crack.

Different cultivars respond differently to cracking due to their morphological make-up [50,51]. Hence, irrigation and soil moisture monitoring are essential in pomegranate farming [48]. Furthermore, the positioning and pruning of pomegranate trees should not expose pomegranate fruit to direct sunlight in order to reduce sunburn, crack and splits. Furthermore, application of borax at the beginning of the fruit set, and irrigation at an appropriate interval according to the cultivar need has been shown to reduce fruit cracking and improve fruit yield [50].

3.2.2. Mechanical and Physical Damage (Superficial Injuries, Bruise Damage and Blemish)

Superficial Injuries

The result revealed that superficial injuries contributed to fruit loss in the farm in varying magnitudes in the three cultivars studied. The highest incidence of superficial injuries was in 'Hershkawitz', with 13.50% of injuries (Figure 2). Nevertheless, it only ranked third in the total causes of loss for 'Hershkawitz'. In 'Acco', it accounted for 11.79% of losses and ranked third in the causes of loss. Superficial injuries contributed to 5.06% of losses and ranked six in the causes of loss for 'Wonderful'. Furthermore, superficial injuries show a very strong positive correlation with decay and crown rot (Table 3). This could be attributed to the fact that superficial injuries to fruit manifested in the form of scratches and cuts of varying shapes, sizes and depth on the rind of the fruit [52], which creates wounds that allow decay and crown rot pathogens to get into the fruit and cause a defect.

The incidence of injury was because of preharvest practices such as pruning, which was done a few days before the fruits were harvested. Furthermore, poor harvesting technique and handling accounted for a considerable amount of injury to fruit. Pomegranate is susceptible to injury due to its high moisture content and succulent nature of its rind.

The result shows that there was a significant reduction in cut injuries as the fruit pickers harvested more fruit and became aware of the impact of the harvesting technique and handling on the fruit; that is, the amount of superficial injuries was as follows: 'Hershkawitz' > 'Acco' > 'Wonderful'. This followed the sequence of fruit picking at the farm and agrees with the fact that injury is a function of fruit harvesting technique and handling, leading to mechanical damage [53].

Bruise Damage

Bruise in 'Acco' accounted for 9.43% (Figure 2) of losses and ranked fourth in the causes of loss for the cultivar. In 'Hershkawitz', bruising accounted for 9.07% of losses and ranked fifth in the causes of loss. For 'Wonderful', the result showed that 5.43% of the losses is attributed to bruise and it also ranked fifth in the causes of loss for the cultivar. The correlation matrix shows that bruise has a very significant positive relationship between decay and insect damage (Table 3). This means that bruised fruit are prone to insect attack because bruising makes the affected spot on the fruit rind soft and susceptible to insect attack. Furthermore, bruise discolored the affected spot on the fruit as the inner tissue of the fruit was damaged. The damaged tissue deteriorates due to the action of hydrolytic enzymes such as cellulases [52] and causes the fruit to decay. This result in a quality loss as it makes the affected area vulnerable to both microbial and insect attack [54].

Mechanical damage is a major cause of bruising, just like an injury. Bruise damage is caused by compression, vibration, and impact during harvesting and handling [14,52]. In this study, bruises were observed to be caused by contact between fruit when the fruit are put into the harvesting buckets and contact with the fruit bin as the tractor conveys the bins along the farm rows with consequent vibration, pressure and thrust on the fruit. Bruise downgrades the quality of pomegranate fruit by damaging the internal tissue of the fruit without physical injury on the rind but manifests in discoloration of the affected area [14].

Hussein et al. [14] reported that pomegranate fruit susceptibility to bruising is in the order of 'Wonderful'> 'Hershkawitz' >'Acco'. However, the variation observed in the outcome of this present study could be attributed to the size of the fruit harvested. 'Wonderful' trees, unlike 'Acco' and 'Hershkawitz', were stripped completely at once giving rise to a high number of undersize fruit, which are not weighty enough to exert high impact energy to cause a bruise.

Blemish

The amount of fruit loss due to blemishes are similar in the three cultivars studied. For 'Acco', it constituted 5.70% of fruit losses, 5.53% in 'Hershkawitz'and 5.69% in 'Wonderful'. The ranking of blemishes in the causes of loss is ninth, seventh and fourth in 'Acco', 'Hershkawitz' and 'Wonderful', respectively. Although it ranked fourth in the causes of loss in 'Wonderful', the result shows that its contribution to loss is low compared to sunburn and crack. Blemish had a strong negative correlation to other loss defects studied, which shows that it occurs independently of other defects in the three cultivars.

Blemishes are a result of many factors such as mechanical damage during the pruning of trees. Furthermore, pomegranate fruits are thrown against branches and each other in windy weather conditions as experienced in the Western Cape, causing the affected fruit to scratch and develop blemishes on the rind. Additionally, preharvest practices, like the application of pesticides and sunscreen, often react to leaf patches and spots that result in blemishes on the affected fruit.

3.2.3. Biological Damage (Insect Damage)

Insect Damage

Insect damage contributed to 6.76% of losses in 'Acco', ranking seventh in the causes of loss in the cultivar. For 'Hershkawitz', it accounted for 3.61% of losses, ranking ninth in the causes of loss (Figure 2). Lastly, 1.43% of losses in Wonderful were due to insect damage and also ranked ninth in the causes of loss for the cultivar. Insect damage has a very strong positive correlation with bruise and also a strong positive correlation with superficial injuries (Table 3), which means that insect damage was high where fruit are susceptible to bruise and superficial injuries. This agrees with the fact that 'Acco', which accounted for the highest incidence of insect damage is also ranked first in bruise damage and second in injury because its rind is softer than 'Hershkawitz' and 'Wonderful', making it more susceptible to insect attack, bruise and injury.

Furthermore, the varying magnitude of damage by insects in the three studied cultivars could also be attributed to the taste of the cultivars, as some insects are known to attack sweet cultivars more than the sour ones. 'Acco' is the sweetest of the three cultivars studied, so it is reasonable for it to account for the highest incidence of insect damage because of its taste. Furthermore, preharvest practices such as the application of pesticides could be another factor to determine the extent of insect attack but were not considered significant in this study, because it is assumed that the farming practices are the same since the study was conducted on one farm.

Insects consume a small portion of fruit, which causes partial loss of fruit in most cases [55]. As a result, the fruit loses its appeal and fails to meet the market standard. Although this present study did not identify the particular types of insects that caused damage to pomegranate fruit, various insects such as Pugnacious ant (*Anoplolepis custodiens*), Mediterranean fruit fly (*Ceratitis capitate*), Soft brown scale (*Coccus hesperidum*), Cocktail ant (*Crematogaster peringueyi*), Common earwig (*Forficula senegalensis*), Kromnek thrips (*Frankliniella schultzei*) and False codling moth (*Thaumatotibia leucotreta*), among others, were identified as the major causes of insect damage to pomegranate fruit in South Africa [56].

3.2.4. Microbial and Pathological Spoilage (Decay and Rots, Alternaria, Crown Rot)

Decay and Rots

Decay and rots are one of the lowest causes of pomegranate fruit losses and waste among the three cultivars studied. In 'Acco', it contributed to 4.09% of loss (Figure 2) and is the lowest source of fruit loss in the cultivar. Although decay and rots ranked sixth in the causes of loss in 'Hershkawitz', they were the highest in the three cultivars studied. It caused 5.74% of the losses in 'Hershkawitz'. Like in 'Acco', decay and rots were the lowest causes of fruit loss in 'Wonderful', accounting for 1.18% of the fruit loss. The correlation matrix result revealed that decay and rots have a significant positive relationship with bruise and injury (Table 3). This entails that pomegranate fruits are more susceptible to decay and rots when bruised or injured. This is because decay and rot-causative pathogens mostly infect fruit through superficial wounds on the rind of the fruit. This reason also applies to the positive relationship between decay and crown rot, which were mostly observed in 'Hershkawitz'.

Decay in pomegranate fruit is caused by a number of microbial pathogens such as Aspergillus fruit rot (*Aspergillus niger*), Grey mold rot (*Botrytis cinereal)* and Blue/Green mold (*Penicillium implicatum*), among others [19]. These pathogens break down the rind of the fruit and ultimately result in decay.

The result revealed that 'Acco' and 'Hershkawitz' had more decayed fruit while 'Wonderful' had a significantly low decay. Apart from the susceptibility of 'Acco' and 'Hershkawitz' to decay and rots due to bruise and injury, selective cultivar breeding by decay-causative pathogens could be another reason for the vulnerability of the cultivars to decay and rot. This assumption is made because there has been a lack of studies to assess the susceptibility of the different pomegranate cultivars to diseases [19].

Alternaria

The total contribution of *Alternaria* to fruit loss in the three cultivars studied, as shown in the results, is low. Its highest occurrence was in Acco with 6.84% of loss (Figure 2). In 'Hershkawitz', it accounted for 4.33% of the loss. For 'Wonderful', *Alternaria* accounted for 2.58% of loss ranking eighth in the total causes of fruit loss in the cultivar. *Alternaria* has a strong relationship with decay according to the correlation analysis (Table 3). In fact, *Alternaria* is a form of decay with a causative pathogen that does not necessarily need bruise or injury to occur. 'Heart rot' disease, also known as *Alternaria*, is caused by the pathogen *Al. alternata*. The disease mostly attacks the inner parts of the fruit, causing it to either completely or partially decay, while the rind of the fruit looks healthy. The affected fruit shows an intense reddish color on the rind and is light in weight compared to the healthy fruit [19].

Although *Alternaria* infection was generally low among the cultivars, the result revealed that 'Wonderful' and 'Hershkawitz' had less fruit affected, while 'Acco' had more. This could be attributed to disease pathogen breeding for the cultivar. It could also be as a result of the morphological development (during flowering) since that is when the disease infection mostly occurs [57].

Crown Rot

The contribution of crown rot to the total fruit loss is relatively low. The highest occurrence was in 'Hershkawtz', with 11.7% of loss and fourth in the cultivar reasons for losses ranking (Figure 2). For 'Acco', it accounted for 6.92% of losses and is fifth in the ranking of causes of loss. Lastly, in 'Wonderful', crown rot contributed 1.38% of losses and is only higher in occurrence than decay among the other causes of loss in the cultivar. It was interesting to note that the negative relationship between crown rot and sunburn was the highest of all the negative correlations. This suggests that crown-rot-causative pathogens may not thrive in high temperatures that result in sunburn. The pathogen responsible for crown rot is *Coniella granati.* The affected fruit shows rotten crown with cream-color in some cases. The rind of the affected fruit also shows the presence of pycnidia [19].

'Hershkawitz' showed the highest incidence of Crown rot, which could be attributed to the tree morphology, since the leaves harbor moisture as they are not spread out like in 'Acco' and 'Wonderful'. *Coniella granati* thrives between the temperature range of 25 to 30 °C [19]. Hence, the leaves of 'Hershkawitz' provide a breeding spot enhancing the growth of the fungi.

3.2.5. Irregular Fruit Size and Shape (Oversize, Undersize and Misshapen)

Oversize

Oversize fruit were noticed only in 'Wonderful', which naturally produces bigger fruit sizes with larger surface area than 'Acco' and 'Hershkawitz'. Some of the fruits are big enough not to fit into the 3.8 kg equivalent carton used for fruit packaging. Such fruit contributed to only 3.67% of the losses in 'Wonderful' (Figure 2). The fruits were removed from the value chain because of their size and could be used for other purposes. Oversize fruit has a strong positive correlation relationship with sunburn and a strong correlation with crack (Table 3). This agrees with the fact that big fruits with a larger surface area are mostly exposed to direct sunlight outside the tree canopy, which results in sunburn. Additionally, fruits with a larger surface area, such as 'Wonderful', are most susceptible to crack due to internal moisture content regulation by the tree and fruit.

Undersize and Misshapen

The result of the study shows that misshapen and undersize fruit accounted for a similar amount of loss in 'Acco' and 'Hershkawitz', with 5.89% and 5.74%, respectively (Figure 2). Undersize and misshapen fruit together contributed to 25.35% of loss in 'Wonderful'. It is important, however, to note that the major contributor to this is undersize fruit. Undersize and mishappen fruit accounted for the second-highest cause of losses in 'Wonderful' after sunburn. It was found that many of the fruits were small and irregular in shape, making them unappealing and not meeting marketing standards. Undersize and misshapen fruit have a very strong negative relationship with bruise, injury and decay in the correlation result, suggesting that fruit are only vulnerable to defects such as bruise, injury and decay when they are fully mature and increase in size.

'Wonderful' has the highest number of small fruit because the trees were striped at once. For 'Acco' and 'Hershkawitz', the fruit were harvested with the harvesting rings to ensure that only fruit of particular size were harvested at each time as the trees were harvested multiple times. Harvesting of 'Wonderful' coincided with when the national lockdown due to COVID-19 pandemic was anticipated in the country. Therefore, the farmer decided to strip the 'Wonderful' trees at once, which resulted in harvesting undersize fruit, causing huge loss.

3.3. Comparative Analysis of Pomegranate Fruit Cultivars Based on Defects

To compare the relationship between pomegranate fruit defects and the cultivars, the defects were subjected to principal component analysis (PCA), and the result was observed in a biplot axes. The relationships between the fruit defects and the cultivars manifested by the short distances and clustering of defects around cultivars (Figure 3). The active and observation variables show that 'Hershkawitz' is more susceptible to injury, crown rot and decay than 'Acco' and 'Wonderful', while 'Acco' is more vulnerable to insect damage, Alternaria and bruise. The result revealed that 'Wonderful' was more susceptible to defects originating from environmental stress than 'Acco' and 'Hershkawitz'. For farm management practices, a dendrogram cluster analysis was used to separate pomegranate cultivars (Figure 4). The two main clusters were differentiated based on their susceptibility to defects. Cluster 1 consisted of 'Wonderful' while 'Hershkawitz' and 'Acco' are in cluster 2. The analysis means that the same loss reduction strategies could be used by the farmer to reduce pomegranate fruit losses for 'Herskawitz' and 'Acco', while 'Wonderful' would require a different loss reduction approach.

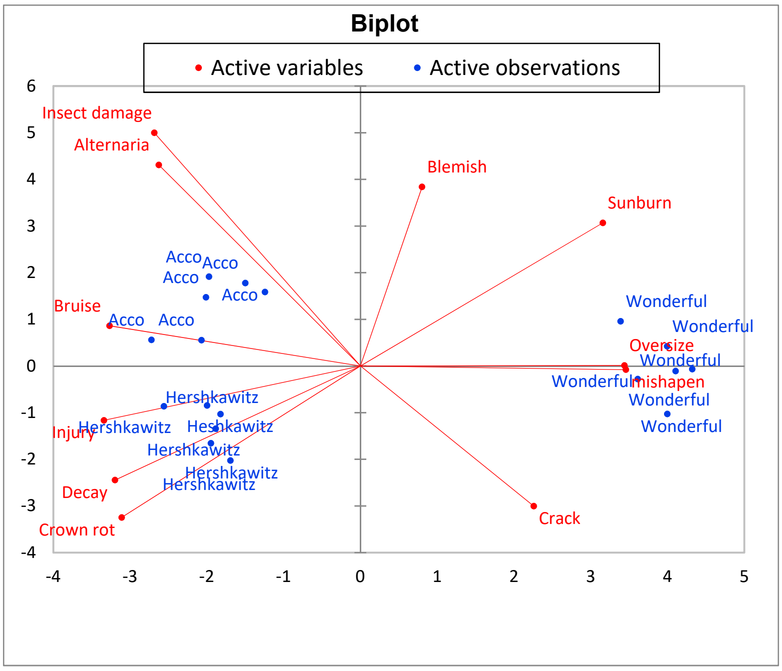

Figure 3. Observation chart showing susceptibility of pomegranate cultivars to different fruit defects. *X*-axis represents F1 (70.45%) loading while *Y*-axis represents F2 (12.91%) loading.

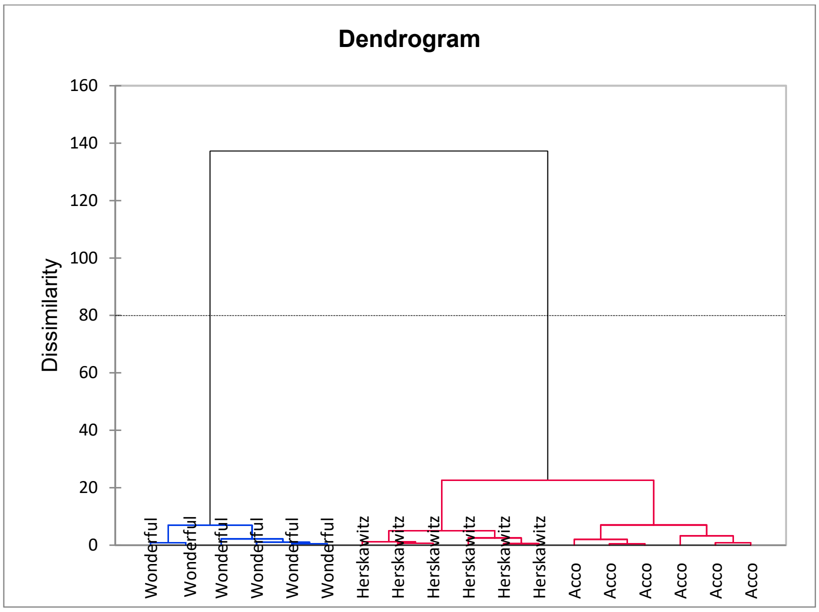

Figure 4. Dendrogram of clusters analysis of three pomegranate cultivars studied based on defects.

Pomegranate fruit defects in the three cultivars studied varied significantly, as shown by their mean and standard error (Table 4). The defects originated from different sources such as mechanical, environmental and biological, among others. The results show that environmental factors are the major causes of pomegranate fruit losses at the case study farm. Environmental factors accounted for the highest incidence of loss with 43.93% of the total loss, followed by losses due to mechanical damage, with 17.99% of the total loss. Fruit losses at the case study farm due to physiological and microbial and pathological factors are close in range and accounted for 13.76% and 14.75% of total losses, respectively. The biological factor considered is insect damage, which contributed to 3.92% of the total fruit loss at the case study farm. Lastly, physical loss due to blemishes contributed to 5.65% of losses.

Table 4. Comparison between pomegranate cultivars on the number of fruit with different defects and percentage of fruit losses in the case study farm.

	Cultivar							
Defects	**Acco (Mean)**	**Acco (Total)**	**Hershkawitz (Mean)**	**Hershkawitz (Total)**	**Wonderful (Mean)**	**Wonderful (Total)**	**Total**	**Loss (%)**
Biological								
Insect damage (mean)	95.17 ± 3.86 [c] *	571	49.17 ± 4.02 [a]	295	20.67 ± 2.76 [b]	124		
Total		571		295		124	990	3.92
Irregular fruit size and shape								
Undersize/malformation	83.00 ± 3.32 [b]	498	78.17 ± 5.44 [b]	469	366.00 ± 6.23 [a]	2196		
Oversize	0.00 ± 0.00	0	0.00 ± 0.00	0	52.50 ± 3.15 [a]	315		
Total		498		469		2511	3478	13.76
Mechanical damage								
Bruise damage	132.83 ± 5.46 [a]	797	123.50 ± 3.25 [a]	741	78.50 ± 3.39 [b]	471		
Superficial injuries	166.00 ± 10.13 [a]	996	183.83 ± 5.06 [a]	1103	73.17 ± 6.12 [b]	439		
Total		1793		1844		910	4547	17.99
Environmental stress								
Sunburn	338.33 ± 8.94 [a]	2030	289.33 ± 5.38 [b]	1736	415.83 ± 3.48 [c]	2495		
Crack and splits	261.00 ± 4.23 [b]	1566	266.00 ± 4.20 [ab]	1596	280.17 ± 5.57 [a]	1681		
Total		3596		3332		4176	11104	43.93
Microbial and pathological								
Alternaria	96.33 ± 2.26 [c]	578	59.00 ± 3.28 [a]	354	37.33 ± 2.79 [b]	224		
Crown rot	97.50 ± 5.86 [a]	585	159.33 ±3.44 [c]	956	20.00 ± 2.07 [b]	120		
Decay and rots	56.67 ± 2.93 [a]	340	78.17 ± 3.22 [c]	469	17.17 ± 2.57 [b]	103		
Total		1503		1779		447	3729	14.75
Physical								
Blemish	80.33 ± 5.59 [a]	482	75.33 ± 4.78 [a]	452	82.17 ± 4.48 [a]	493		
Total		482		452		493	1427	5.65

* Mean values in the same row followed by different letters ([a], [b], [ab] and [c]) indicate significant differences ($p < 0.05$).

4. Discussion

4.1. Economic, Environmental and Resource Impacts

The amount of fruit lost at the case study farm has huge financial implications on the farmer and the value chain actors. Furthermore, there are sustainability concerns of wastage in the bioeconomy [58,59] in terms of impact on resource use and the natural environment. The implication of the findings of this study were presented based on the magnitude of incidence of loss at the case study farm in Wellington, Western Cape Province, South Africa and retail price in South Africa. This is to show the potential value of production inputs and natural resources that are wasted to produce the lost pomegranate fruit. Based on the findings of this study, the economic, environmental and resources impacts of pomegranate losses at the case study farm, which was escalated to the national level (South Africa) and global level were summarised in Table 5. The extrapolation to the global level is limited since the data are from only one case study farm. However, the extrapolations of the case study farm data to South Africa and globally have been made to give an indication of the magnitude of fruit loss and associated socio-economic impacts, which could be used to raise awareness on the importance of reducing fruit losses at the farm level. Typically, the amount of on-farm fruit loss will vary depending on a range of factors including harvest season, production practices, harvest management practices, weather conditions and the intended market for harvested fruit (e.g., fresh fruit versus juice).

Table 5. Summary of the magnitude of pomegranate fruit losses impacts at the case study farm, South Africa and global levels.

Factor	Case Study Farm	South Africa	Global
Production area (ha)	17.60	1024.00	98,701.29
Production volume (tonnes) *	677.60	39,424.00	3.80×10^6
Average loss (%)	17.38	17.38	17.38
Retail price (R/kg) [a]	89.99	89.99	89.99
Estimated physical and economic losses			
Physical loss (tonnes)	117.76	6851.89	660,440.00
Monetary loss (ZAR)	10.50×10^6	616.60×10^6	59.43×10^9
Environmental impacts			
Estimated GHG emission (CO_2 eq) [b]	56.50×10^3	3288.00×10^3	317.01×10^6
Estimated energy used (MJ) [c]	718.00×10^3	41.79×10^6	4.02×10^9
Resource impact			
Water footprint (m^3) [d]	107.10×10^3	6235.20×10^3	601.00×10^6
Equivalent land used to produce lost fruit (ha)	3.00	177.97	17,174.02

* Production statistics are based on [18]. [a] Supermarket retail price in Stellenbosch, Western Cape, South Africa. [b,c] Impacts per unit fruit produced estimated from [39]. [d] Impact per unit fruit produced estimated from [40]).

The price of pomegranate fruit at the supermarkets means that ZAR88.99 (USD 5.26) is lost per 1 kg of the lost pomegranate fruit. Based on the annual average loss of 17.38% of the harvested fruit (Table 5) at the case study farm level, which amounted to 117.76 tonnes, the monetary loss of the total annual production was estimated at ZAR 10.5 million (USD 618,715.34). During the production of pomegranate fruit, GHGs are emitted into the atmosphere. Based on the findings of this study, the pomegranate losses at the farm level were estimated to emit about 56,524.80 t of CO_2 eq (Table 5). To sink this amount of CO_2 eq, it would require planting at least 1.4 million trees at 0.039 metric ton CO_2 per tree planted [60]. Furthermore, about 718,336.00 MJ of energy and 107,161.60 m^3 of freshwater were wasted (Table 5). The wasted freshwater could meet the daily water requirement of about 5871 people for a year at 0.05 m^3 consumed per person per day [61]. Lastly, about 3 ha of land was used to produce the lost fruit.

Moreover, the impacts of losses were estimated at the national (South Africa) level based on the data from the case study farm, and losses at the national level were estimated at 6851.89 tonnes (Table 5). The monetary loss of the total annual production was estimated at R616.60 million ($36.60 million). Losses at the national level were found to emit about 3.2 million t of CO_2 eq (Table 5). To sink this amount of CO_2 eq, it would require planting at least 82 million trees at 0.039 metric ton CO_2 per tree planted [60]. Additionally, about 41.79 million MJ of energy and 6.23 million m^3 of freshwater were wasted (Table 5). The wasted freshwater could meet the daily water requirement of about 341,369 people for a year at 0.05 m^3 consumed per person per day [61]. Lastly, about 177.97 ha of land was used to produce the lost fruit.

Furthermore, the impacts of pomegranate fruit losses were estimated at the global level using the incidence of losses and retail price in South Africa. This assumes a 17.38% loss of total production globally, which was estimated at 660,440 tonnes (Table 5) and retail price of ZAR 88.99/kg ($5.26/kg). The monetary loss of the total annual production was estimated at ZAR 59.43 billion ($3.4 billion). Based on the estimation, about 317 million t of CO_2 eq (Table 6) was emitted annually due to losses of pomegranate fruit. To sink this amount of CO_2 eq, it would require planting at least 8.1 billion trees at 0.039 metric ton CO_2 per tree planted [60]. Furthermore, about 4.02 billion MJ of energy and 601 million m^3 of freshwater were wasted (Table 5). The wasted freshwater could meet the daily water requirement of about 32.9 million people for a year at 0.05 m^3 consumed per person per day [61]. Lastly, about 17,174.02 ha of land was used to produce the lost fruit. The research findings showed that postharvest losses of pomegranate fruit do not only cause loss of revenue through lost income but also causes environmental stress and unsustainable utilization of natural resources and the emission of GHG, which drives global warming.

Table 6. Summary of selected nutritional impacts of pomegranate fruit losses at the case study farm, national level (South Africa) and global levels.

	Case Study Farm		National (South Africa)		Global		
Nutrition Factor	**Amount Lost ($mg100^{-1}$ g) ***	**Nutritional Loss (per capita/day) ****	**Amount Lost ($mg100^{-1}$ g) ***	**Nutritional Loss (per capita/day) ****	**Amount Lost ($mg100^{-1}$ g) ***	**Nutritional Loss (per capita/day) ****	**Role of Nutrient in Human Health**
Fibre	58.88 ##	2.00	3425.94 ##	137.00	330×10^{3} ##	13,224.00	Digestibility [62]
Carbohydrate	1165.82 ##	9.00	67,833.71 ##	522.00	654×10^{4} ##	50,353.00	Energy source [63]
Protein	164.86 ##	4.00	9592.64 ##	209.00	925×10^{3} ##	20,123.00	Energy source [64]
Iron	35.32	2.00	2055.56	114.00	198×10^{3}	11,020.00	Oxygen transport [65]
Ascorbic acid	1766.40	24.00	102,778.35	1370.00	991×10^{4}	132,240.00	Antioxidant [66]
Calcium	3532.80	4.00	205,556.70	206.00	198×10^{5}	19,836.00	Bone formation [67]
Magnesium	1413.12	5.00	82,222.68	265.00	793×10^{4}	25,595.00	Better lung function [68]
Sodium	471.04	1.00	27,407.56	14.00	264×10^{4}	1322.00	Blood pressure regulation [69]
Potassium	20,136.96	4.00	1,171,673.19	249.00	113×10^{6}	24,056.00	Fluid regulation [70]

* Amount lost is based on [3]. ** Nutritional loss is based on [41]. ## Amount lost are estimated in $g100^{-1}$ g.

4.2. Nutritional Impacts

The loss of pomegranate represents a huge loss of nutrients owing to its numerous nutritional benefits. Table 6 presents some of the nutrients that are lost due to postharvest losses at the case study farm. This is coming in a period where the COVID-19 pandemic has drastically impacted the source of livelihood of many in the country and, indirectly, their ability to afford healthy and nutritious food. Based on the annual loss of pomegranate fruit at the farm, the loss of nutrients associated with lost fruit could meet the fiber, carbohydrate, protein and iron daily recommended intake of 2, 9, 4 and 2 people, respectively. Similarly, the lost vitamin C (ascorbic acid) content in fruit lost on-farm is sufficient to meet the daily intake of 24 people.

The nutritional impacts of pomegranate fruit losses were also estimated at the national (South Africa) level (Table 6) using incidence of losses at the case study farm. For instance, based on the annual losses of pomegranate fruit at the farm, the amount of ascorbic acid (which has an antioxidant property [66] associated with lost fruit, could meet the daily recommended intake of 1370 people in the country. Furthermore, protein and carbohydrate, which are good sources of energy [63] that were lost in the lost fruit could meet the daily required intake of 209 and 522 people, respectively. Nutritional loss was also estimated at the global level. The research findings showed that postharvest losses of pomegranate fruit contribute to global food and nutritional insecurity.

5. Conclusions

This study revealed that pomegranate fruit loss ranged between 15.3 to 20.1% of the harvested fruit at the case study farm. This amounted to an average loss of 117.76 tonnes of pomegranate fruit harvested per harvest season. This amount of fruit is removed from the value chain and sold mainly at a low value for juicing and other purposes. The main causes of on-farm fruit loss are environmental factors. In the three pomegranate cultivars studied, sunburn and crack were identified as the leading cause of fruit loss, accounting for about 43.9% of all on-farm losses. Furthermore, mechanical damage, including bruising and injury and microbial factors (causing decay and spoilage) contributed to significant fruit loss. The magnitude of on-farm fruit loss of harvested 'Acco' was 15.8 to 16.5%, 15.3

to 16.2% for 'Hershkawitz' and 19.7 to 20.1% for 'Wonderful'. The fact that two different harvest methods were used is a limitation of the study—both 'Acco' and 'Herskawitz' were harvested based on uniform fruit size while 'Wonderful' was strip-harvested due to travel restrictions during COVID-19 pandemic.

Considering the various impacts of postharvest losses at farm, national and global levels, there is no doubt that reducing postharvest losses is a sustainable way to mitigate global warming and enhance food and nutrition security, as well as increase revenue for food system actors. Lastly, strategies to control and reduce pomegranate fruit losses and waste at the farm level should be tailored to environmental factors (sunburn and cracking) and mechanical damage (bruising and other defects), since they account for the highest sources of fruit losses. This will ensure improved revenue to farmers, sustainable use of natural resources, reduction of the environmental impacts of fruit production and greater availability of quality fruit, which contribute to improving nutritional security for healthy life and wellbeing.

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