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A comparative analysis using a forest resource *Opuntia ficus-indica* L. (prickly pear) and *Pyrus communis* (common pear) a commercial fruit: Implications on nutrition and sustainability.

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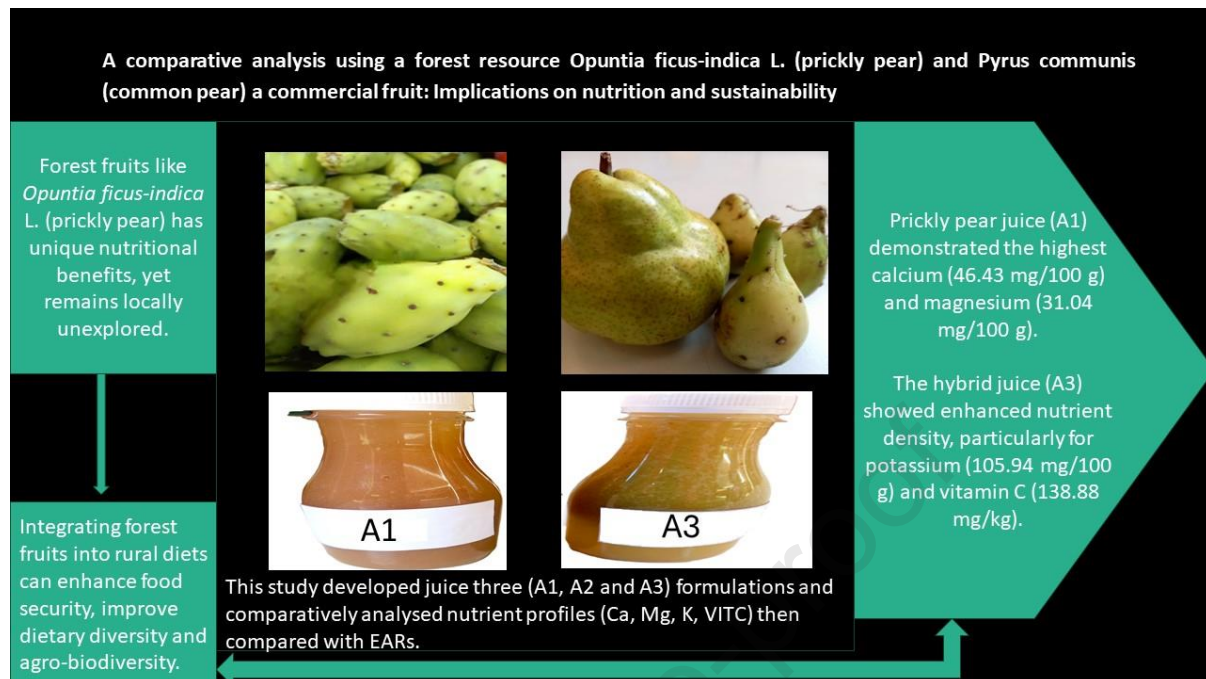
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Abstract

Malnutrition and food insecurity persist in rural communities, where limited access to nutrient-rich foods exacerbates health challenges. Indigenous fruits like *Opuntia ficus-indica* L. (prickly pear) and *Pyrus communis* (common commercial pear) provide unique nutritional benefits, yet their potential synergy remains unexplored. This study analysed nutrient profiles of juices made from these fruits individually and in a hybrid formulation. Prickly pear juice (A1) demonstrated the highest Calcium (Ca) (46.43 mg/100 g) and Magnesium (Mg) (31.04 mg/100 g) concentrations, while common pear juice (A2) was a superior source of Potassium (K) (56.72 mg/100 g). The hybrid juice (A3) showed enhanced nutrient density, particularly for potassium (105.94 mg/100 g) and Vitamin C (VITC) (138.88 mg/kg), contributing up to above 100% of the Estimated Average Requirement (EAR) for women. Nutrient contribution to DRIs was statistically significant ($p < .005$) for Ca, Mg, K and VITC for A1-A3 juice concentrations. The hybrid juice also displayed the highest composite Nutrient Density Index (NDI) (0.7480 mg/kcal), supporting its potential as a nutrient-dense beverage to combat nutrient deficiencies. Integrating these fruits into rural diets can enhance food security, promote agroforestry, and improve dietary diversity. Policy recommendations include incentivizing indigenous fruit cultivation and incorporating hybrid products into nutrition programs to address malnutrition and foster sustainability.

Keywords: indigenous forest fruits, *Opuntia ficus-indica* L., nutrient density, food security, sustainable food systems

GRAPHIC ABSTRACT



STUDY HIGHLIGHTS

- Prickly pear provides high calcium, magnesium, and antioxidants for arid rural diets.
- Nutrient analysis supports prickly pear's inclusion as nutrient-dense forest fruit.
- Nutrient Density Index (0.7480 mg/kcal) was observed for the hybrid juice.
- Integration of indigenous and commercial fruits enhances food security and biodiversity.
- Hybrid juice of prickly pear and common pear boosts nutrition and complements food systems.

1. Introduction

Malnutrition and food insecurity remain major life-threatening issues in many rural communities, where access to a diverse range of nutrient-rich foods is often limited [1]. One possible solution to this challenge is to tap into the potential of indigenous and underutilized wild fruits, which have a high nutrient density but are frequently overlooked [2]. This is particularly true in rural areas, where limited access to varied food sources due to the geographical context and increasing cost of food exacerbates malnutrition. Consequently, there is growing recognition of the need to promote indigenous fruits as part of a broader strategy to enhance food sovereignty and improve the resilience of rural food systems [3, 4]. Among these neglected fruits is the prickly pear (*Opuntia ficus-indica* L.), a hardy plant that thrives in arid environments [5, 6]. Traditionally consumed by many rural communities, the prickly pear is known for its high levels of dietary fibre, vitamins, and antioxidants [7]. However, despite its potential to offer nutritional value and versatility in local diets, it remains underutilized. On the other hand, the common pear (*Pyrus communis*), widely consumed around the world, is recognized for its nutritional value [8]. Yet, little research has compared its role in rural nutrition with that of indigenous fruits like the prickly pear.

Recent studies [9, 10] have highlighted the potential of forest-based foods and underutilized edible resources in addressing global food security challenges. The role of indigenous fruits in contributing to diversified diets, particularly in regions affected by food insecurity, has been increasingly recognized. For example, wild fruits like *Adansonia digitata* (baobab) [11] and *Irvingia gabonensis* (bush mango) [12] have gained attention for their nutritional and ecological benefits. This growing body of research underscores the importance of incorporating underutilized indigenous species, like prickly pear, into food systems as a means of improving food and nutrition security and, thus sustainability. This study accentuates these literature findings by exploring the significant role of *Opuntia ficus-indica* L. particularly and *Pyrus communis* when improving dietary intake within rural communities.

This lack of comparison between commercially available fruits and lesser-known indigenous species raises an important question: Could combining both types of fruits improve food and nutrition security in rural areas? While the pear is a well-established part of many diets, the *Opuntia ficus-indica* L. offers unique advantages in terms of its resilience to harsh environmental conditions and its cultural significance in rural communities. Understanding

how these two fruits complement each other could lead to valuable insights that can improve community understanding, which was factored in when designing the formulation of this investigation. In addition to its well-documented role in agro-ecological settings, *Opuntia ficus-indica* L. plays a significant role in forest-adjacent and marginal lands, especially in semi-arid environments [7]. As a resilient species, it is often found in regions where forest ecosystems are under threat due to desertification or degradation [7]. Integrating *Opuntia ficus-indica* L. cultivation into agroforestry systems can promote reforestation efforts by stabilizing soil, improving water retention, and creating habitats for wildlife, making it a valuable species for both food production and environmental restoration in these areas [13]. Forest-adjacent lands that support prickly pear cultivation offer a potential pathway for sustainable forest management, helping to rehabilitate degraded landscapes and reduce pressure on existing forests [13]. This paper aimed to comparatively examine the nutritional benefits of *Opuntia ficus-indica* L. as a native fruit species that is part of the local ecosystem, with a more commercially produced fruit species that is often found in other regions of the country. Considering that both these fruits are often locally referred to as pears, therefore, the study envisaged the significance of this exploration as part of making a distinction on the benefits of a forest fruit pear to shift its positioning in the local community.

2. Characterization of selected fruit species for processing utilization

2.1 Characteristics of *Opuntia ficus-indica* L. (Prickly Pear) as a wild fruit species

Opuntia ficus-indica L. commonly known as prickly pear, is a cactus species native to arid and semi-arid regions. Its fruit, which comes in a variety of colours including green, yellow, red, and purple, is covered in tiny spines known as glochids. Inside, the fruit is spongy, and juicy and contains small edible seeds [14]. The prickly pear is widely known for its ability to thrive in harsh environments, making it an essential resource in drought-prone rural areas [7, 13]. Traditionally consumed in many cultures, it offers both nutritional and medicinal benefits [7, 15-17]. Locally prickly pear is referred to as uputshu or idolofiya (in the isiZulu language) and has been traditionally consumed and used for medicinal properties.

Indigenous people who often were grazing livestock consumed this forest wild fruit regularly as a source of food and they often formed part of their local food system [18]. The cactus nature of the prickly pear has been used as a hedge plant to also protect livestock in

indigenous kraal settings [19]. According to the Alien and Invasive Species Regulations (AIS), National Environmental Management: Biodiversity Act (Act No 10 of 2004), *Opuntia ficus-indica* L. is classified under category 1b with ornamental value. This category has set controls for its removal and destruction, the planting of this forest fruit is only excepted for the purposes of human consumption only [20].

Opuntia ficus-indica (prickly pear) is typically grown in arid and semi-arid regions with minimal water requirements, making it well-suited for regions with limited water resources [21]. The fruit is usually cultivated in open fields, though it is often grown in sheltered environments or under partial shade to protect it from extreme weather conditions and to improve fruit yield [22]. In commercial production, prickly pear is not typically grown in greenhouses, but it is often planted on sheltered land or raised beds to ensure optimal fruit growth and facilitate easier harvesting [19].

Prickly pears are classified as non-climacteric fruits; however, a climacteric-like rise has been observed at various developmental stages before harvest [23]. Their post-harvest lifespan is relatively short at ambient temperatures but can extend to 4–6 weeks when stored at 6–8°C [24]. These fruits are highly susceptible to chilling injury (CI) at temperatures below 6°C, especially when exposed to ripening and harvest temperatures exceeding 30°C [24]. CI disrupts metabolic pathways, leading to a loss of firmness, accelerated degradation of organic compounds, and alterations in flavour and taste, including increased acetaldehyde and ethanol levels [24].

In terms of post-harvest handling, prickly pear fruit is carefully harvested by hand to avoid damaging the delicate skin, and it is then transported to processing facilities where it undergoes ripening or direct processing, depending on the intended use [19]. The shelf-life of prickly pear is relatively short, as the fruit is highly perishable, and thus, it requires prompt processing or refrigeration to maintain its quality [19].

2.2 Nutritional and medicinal benefits of *Opuntia ficus-indica* L. (Prickly Pear)

The prickly pear has been hailed for its robust nutrient profile, which makes it particularly suitable for addressing certain micro-nutrient deficiencies common in rural areas such as vitamin C deficiency [25]. There is existing evidence of its high concentration of vitamin C which is vital for immune health, collagen production, and the maintenance of skin, bones,

and teeth [26]. Vitamin C acts as a powerful antioxidant, helping to neutralize harmful free radicals in the body and reduce oxidative stress [27]. Various authors agree that the fruit's dietary fibre, primarily in the form of pectin, supports digestive health by facilitating regular bowel movements and preventing constipation [7, 13, 15, 19, 26]. High fibre intake is also associated with reduced risks of chronic diseases such as type 2 diabetes and heart disease [28]. Other benefits include the presence of a variety of phytonutrients, including betalains, which contribute to its anti-inflammatory and antioxidant properties [29]. Smeriglio et al. (2021) underscores that betalains have been shown to reduce inflammation, protect against neurodegenerative diseases, and promote overall well-being, making this fruit a valuable component of a health-conscious diet in regions where healthcare access is limited. Prickly pear seeds are rich in polyunsaturated fatty acids, which are essential for maintaining heart health and promoting brain function [13, 15, 29]. These fatty acids are also crucial for the absorption of fat-soluble vitamins (A, D, E, and K), making the fruit's overall nutrient profile well-balanced for supporting long-term health outcomes in resource-limited settings [13, 15, 29].

In addition to its nutritional value, the prickly pear has been used traditionally in many cultures for its medicinal properties. The fruit and pads (cladodes) are used to treat a variety of ailments, including inflammation, gastric issues, and skin problems [16]. Its anti-inflammatory properties make it an effective treatment for conditions such as arthritis, while its mucilage (a sticky substance found in the pads) can be used as a natural remedy for digestive problems, including gastritis and ulcers [30]. There is still a paucity of literature that exposes its significant role within the food system as opposed to *Pyrus communis* which has a better market positioning because of its global footprint.

2.3 Characteristics of *Pyrus communis* (Common Pear) domestically cultivated

Pyrus communis, commonly referred to as the common pear, is a deciduous tree that produces a soft, sweet, and juicy fruit widely cultivated in temperate regions [31]. Pears are the third largest fruit produced in South Africa with the latest statistics showing 475,000 MT (523597,873 tons) of total produce and is also largely open for the export market [32, 33]. The fruit has a characteristic bell shape and is typically green or yellow, although some varieties have a red blush. Pears are rich in dietary fibre, vitamins, and antioxidants, making them a popular choice for both fresh consumption as a fruit and processable for juice

production [34]. Pears are an important commercial fruit with global appeal, and they play a significant role in rural economies through agriculture and trade [34].

Pears are typically grown in temperate climates with well-defined seasons, requiring a cold dormancy period to promote flowering and fruit development [31]. In commercial production, common pear trees are generally grown in orchards, where they are carefully spaced to ensure proper air circulation and sunlight exposure for optimal growth [34]. Pears are grown in both sheltered and open field environments, with many orchards utilizing trellis systems or espalier methods to manage tree growth, increase fruit yield, and facilitate easier harvesting [31]. In some cases, pears may also be grown under shade netting or in areas with controlled irrigation systems to reduce the effects of drought and temperature extremes [34].

Regarding post-harvest handling, pears are harvested by hand at their peak ripeness, which varies depending on the specific variety. After harvesting, the fruit is typically subjected to cold storage (at temperatures around 0-4°C) to slow down ripening and extend shelf life until it reaches the processing or consumer stage [35]. Pears are highly perishable, and refrigeration is critical to maintain their quality, texture, and nutritional attributes before processing [31].

2.4 Nutritional Benefits and agricultural benefits of *Pyrus communis* (Common Pear)

The common pear, *Pyrus communis*, is also a significant source of nutrition, known primarily for its digestive benefits due to its high fibre content [36]. A medium-sized pear contains about 6 grams of fibre, which is more than 20% of the daily recommended intake [37]. This high fibre content promotes gut health by feeding beneficial bacteria in the digestive tract, which in turn supports immune function and overall well-being [9, 37, 38]. Pears are a low-calorie fruit, yet they provide essential vitamins and minerals, including potassium, which helps regulate blood pressure by counteracting the negative effects of sodium [39]. Potassium also supports muscle function and nerve signalling, which are critical for maintaining cardiovascular health [40]. The high antioxidant profile found in them has been shown to help combat oxidative stress and reduce the risk of chronic diseases such as cancer, cardiovascular disease, and type 2 diabetes [41]. Flavonoids, a type of antioxidant found in pears, are particularly beneficial for reducing inflammation and improving heart health. Studies have shown that consuming pears regularly can lower the risk of stroke by as much as 52% [42]. Both fruits have been shown to possess antioxidant properties.

From an agricultural perspective, pears are a highly marketable fruit with global demand, making them an important economic crop in many countries [43]. Pears are relatively easy to grow and can be cultivated in a variety of soil types, making them an adaptable crop for rural farmers [44, 45]. Their integration into local markets and export chains contributes to economic growth and can provide income for rural communities [44, 45]. Furthermore, pears have a long shelf life when stored properly, making them a reliable food source that can be stored and consumed throughout the year [36].

While prickly pear offers resilience and traditional medicinal uses [46], the common pear brings broader market appeal and consistent supply [44]. This is an important consideration as we globally deal with the complexity of the food system due to climate change impact whilst also encountering with the increasing cost of fruits as food source. A hybrid juice formulation would not only provide a nutritionally rich beverage but also foster sustainable agricultural practices by promoting the cultivation of both indigenous and commercially viable fruits.

Although *Opuntia ficus-indica L.* and *Pyrus communis* are both recognized for their nutritional benefits, little to no studies have directly compared them or explored the potential benefits of creating hybrid products in South Africa. Most research has focused on the individual advantages of these fruits [43, 47], without considering the synergies that could arise from combining them. Moreover, while the prickly pear has long been acknowledged for its nutritional value and environmental resilience, it has yet to be fully integrated into mainstream agricultural systems or rural food strategies. Finally, by exploring the potential for hybrid fruit products to enhance nutrition, this research aligns with initiatives to revitalize indigenous foods and integrate them more fully into rural diets. Pear-based agro-ecosystems were considered since both fruits were grown from different locations hence, the promotion of the utilization of the forest fruit was broadly considered.

3. Materials and methods

3.1 Study Area (Geographical Setting of the Study)

This study was conducted in rural areas of the South Coast Region in the Harry Gwala District Municipality in KwaZulu-Natal, South Africa, where both indigenous and commercial fruits such as the prickly pear (*Opuntia ficus-indica L.*) and common pear (*Pyrus communis*) are

cultivated. The region is characterized by a subtropical climate that supports the growth of a wide variety of fruits [48]. This area experiences warm, humid summers and mild, cool winters, making it suitable for diverse agricultural practices.

The South Coast Region in KwaZulu-Natal in the town called Highflats (Fig. 1) is located between latitudes 30.0°S and 30.8°S and longitudes 30.2°E and 31.0°E in a dissected plateau (947 m to 1075 m). Locally this town is called kwaQgwathaza (historically named after a local farmer) in the isiZulu language spoken by the people. The terrain is primarily coastal, with rolling hills and valleys that facilitate fruit cultivation. These rural areas are home to small-scale farmers who depend on vegetable and fruit production for their livelihoods, as well as for enhancing nutrition and food security within their communities. Highflats has a mean annual precipitation within the ambit of 800 to 870 mm [49].

In terms of accessibility, this region is serviced by a network of secondary roads, connecting it to larger commercial hubs such as Durban (a metropolitan city which is among one of the largest municipalities in the country). Durban lies approximately 100 km to the north. The geographical setting of this study is significant due to the unique agroecological conditions that support both indigenous and commercial fruit production, providing an ideal context for evaluating the role of these fruits in enhancing rural nutrition and sustainability.

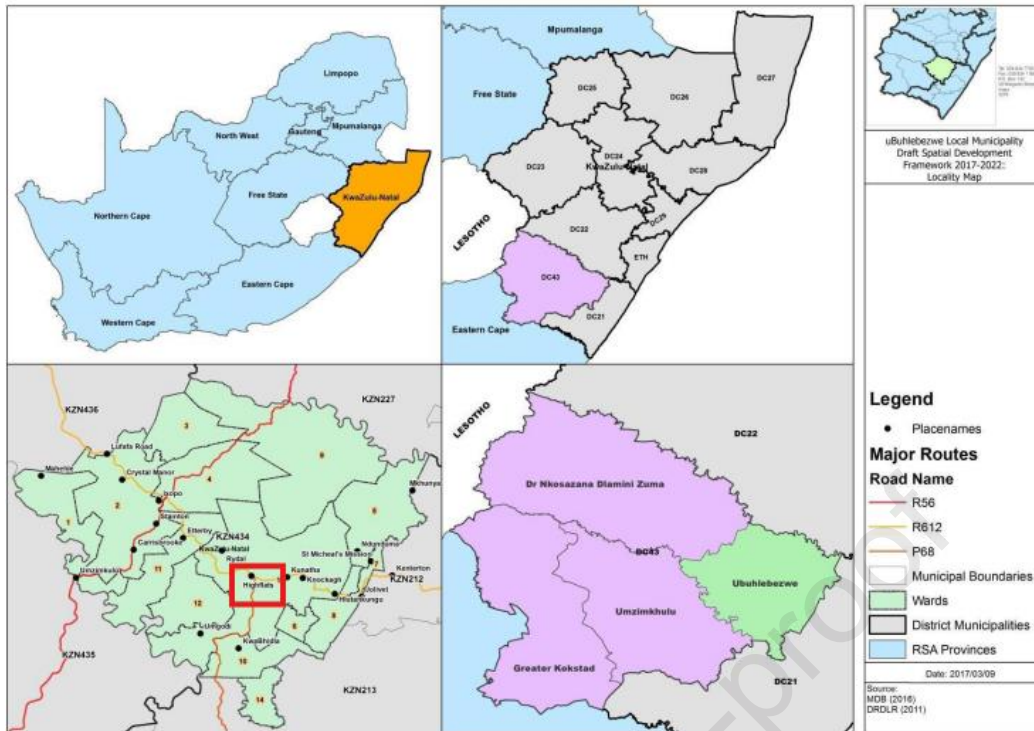


Fig. 1. Map showing High flats Study Area (Source: [50]).

3.2 Research Design

The study was an experimental production using wild fruit *Opuntia ficus-indica* L. which was compared with common pear (*Pyrus communis*) to develop juice formulations that will reveal nutrient density per varied sample. A comparative analysis used a formulation and was calculated based on nutrient contribution per product profiling and for human consumption.

3.3 Preliminary process of fruit sourcing, post-harvesting handling and storage

The fruit is often harvested and consumed by the youth during periods of grazing livestock and fetching water from nearby rivers and streams. The harvesting season was around March 2024, which is the end of summer. Fruit selection was based on its easy access locally, for consumption as a local forest fruit and often less focus for harvesting is associated with nutritional value and medicinal properties it possesses. However, this study mainly focused on the exploration of its nutritional value to better position this forest fruit for the community. The fruit samples were collected on the South Coast of KwaZulu-Natal, specifically from a central forest area used for livestock grazing, located near rural households practising subsistence farming. These fruits, particularly the prickly pear (*Opuntia ficus-indica* L.), grow wild in this region, and traditional methods of harvesting have been passed down through

generations. To collect the fruit, a wire was used to pick the prickly pear from the cactus plant, and the fruits were placed into sackcloth bags. Once gathered, water from a nearby river was poured over the sack, and the fruit was rubbed against the cloth to remove the tiny, barbed thorns known as glochids. Rubber gloves were worn throughout the process to protect against potential skin irritation caused by the thorns.

The study focuses on experimenting with two distinctive plant species one being *Opuntia ficus-indica* L. to determine the nutritional value of magnesium (Mg), calcium (C) and vitamin C (VIT C) for three juice varieties coded [prickly pear (A1), common pear (A2), and a hybrid of both (A3)]. The purpose is to expose the nutrient profile using explorative innovative applications of this forest fruit which has less exposure as opposed to common pear to raise awareness of its nutritional significance. A comparison was made with *Pyrus communis* (Packham's Triumph cultivar) referred to as a pear which is a deciduous fruit largely produced commercially and predominantly grown in the West Cape Province of the country.

The purpose of the experiment was to distinctively compare each sample nutrient profiling and then combine the fruits to determine significant contributions as an explorative measure for product development. The narrative behind this exploration is the importance of closing existing knowledge gaps of the benefits of *Opuntia ficus-indica* L that might have not been documented scientifically for the context of the study setting so that the local community is fully capacitated with these benefits.

Fig. 2 depicts the sourcing and handling processing of prickly pear from the local forest as a forest resource for processing, including factors of ensuring harvested produce quality is preserved. The handling of prickly pear when harvesting and processing requires specific techniques to prevent skin irritations. This highlights the proficiency required when handling forest fruits that might have implications on the frequency of them being harvested by locals. This research paper has utilized a forest fruit and a common fruit with somehow similar characteristics by using freshly formulated juices, whilst following efficient protocols for product development. A cactus pear from the cactus family (*Cactaceae*) was used as the main focal ingredient for exploration and the rose family (*Rosaceae*) common pear was included for comparative purposes. The handling of *Pyrus communis* was less complex since it was sourced from a local market and is part of a modern value chain system.

Agro-biodiversity: Linking the nutritional value through the utilization of *Opuntia ficus-indica* L. as a forest resource

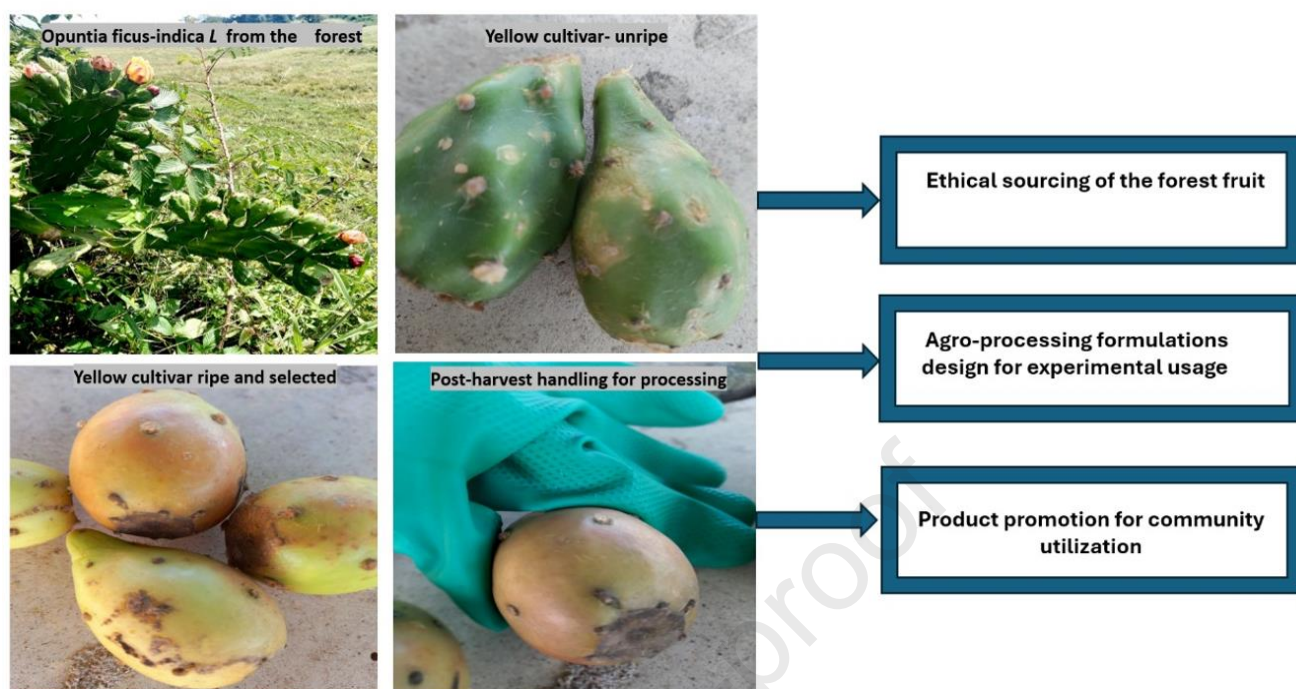


Fig. 2. Prickly pear sourcing and post-harvest handling for processing.

3.4 *Opuntia ficus-indica* L. and *Pyrus communis* product formulation procedure

Opuntia ficus-indica L. and *Pyrus communis* were subjected to different storage conditions due to their distinct post-harvest ripening behaviours and pre-storage histories. *Opuntia ficus-indica* L. samples were transported to the food laboratory and stored at room temperature (27°C) for seven days to allow for controlled ripening. This was necessary because *Opuntia ficus-indica* is a climacteric fruit, meaning it continues to ripen after harvest through ethylene production. Room temperature storage enhances juice yield, sensory attributes, and bioactive compound availability, making the fruit more suitable for processing. Furthermore, the selected storage period was within the acceptable range to prevent excessive deterioration or microbial spoilage while ensuring optimal ripening. Conversely, *Pyrus communis* had already been exposed to cold storage before procurement. Since abrupt temperature changes can negatively impact fruit quality, it was kept at refrigeration temperature (4°C) to prevent rapid biochemical changes, excessive softening, or spoilage before processing. Refrigeration also helped maintain its structural integrity and nutritional properties, ensuring consistency in the final product formulation. Before processing, both fruits were carefully inspected to ensure that microbial spoilage and overripening had not occurred, thereby maintaining the quality and reliability of the formulated juice products.

Three juice samples were prepared using *Opuntia ficus-indica* L. (prickly pear) and *Pyrus communis* (Packham's Triumph pear) as the primary fruit ingredients which are reflected in Fig 3. The prickly pear had a low susceptibility to enzymatic browning, while the common pear required placement in a water and lemon solution to prevent oxidation. The formulation for each juice sample was as follows:

- Sample 1 (coded A1): Prickly pear was used exclusively, with 300g of freshly harvested fruit processed into a 250ml bottled juice serving.
- Sample 2 (coded A2): Common Pear was used as the sole ingredient, with 300g of pear fruit processed into a 250ml bottled juice serving.
- Sample 3 (coded A3): A combination of prickly pear and common pear, mixed in equal proportions (1:1). A total of 150g of each fruit was used to prepare a 250ml bottled juice serving. This formulation was created to innovatively complement the flavour attributes of the selected fruits through a blended product.

All samples were processed and stored at refrigeration temperature (4°C) to preserve freshness. Fig. 3 provides pictorial view on the formulations derived from these fruits, which were then subjected to nutritional analysis.

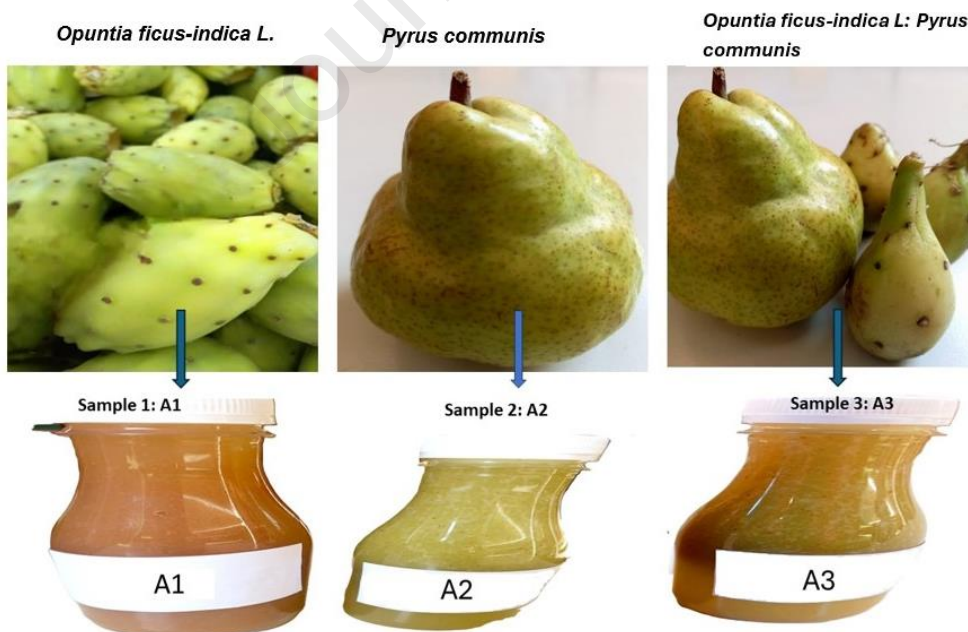


Fig. 3. Illustration of A1-A3 juice formulations with selected fruit varieties.

This research study is premised on the hypothesis that the variation of these formulations will show the forest-sourced fruit to have a higher nutrient density than the other formulations through a comparative nutritional analysis for profiling.

3.5 Data Analysis

3.5.1 Nutritional Analysis/ Nutrient Profiling

After the samples were carefully prepared and stored, the nutrient profiles were analysed for nutrient profiling. The three formulations were assessed for Calcium (Ca), Magnesium (Mg), and Potassium (K) using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) instrument. The NMKL No: 186 method was employed to detect these nutrients accurately. Vitamin C (Ascorbic acid) concentrations were measured using High-Performance Liquid Chromatography with Ultraviolet Diode Array Detection (HPLC UV DAD), following the method outlined in Food Chemistry 52 (1995) and Ruckermann, 1980 (Z. Lebensm. Unters. Forsch., № 171) for Vitamin C analysis. Nutritional content for all samples was analysed per 100g/mg units to determine the mean values of the selected nutrients. To assess the potential impact of the formulations on nutrition security, Dietary Reference Intakes (DRIs) were used to evaluate each juice's significant contribution to the required dietary recommendations. Data was compared against the DRIs for individuals aged 51–70 years, focusing on the Estimated Average Requirement (EAR) and Adequate Intake (AI) for the various nutrients analysed [51-53]. For some nutrients requirements between men and women varied except for potassium. Calculations reflected as mean values were considered gender differences to ensure appropriate recommendations.

3.5.2 Statistical Analysis

The statistical analysis calculated the mean and standard deviation for the nutrient content of the three juice formulations: prickly pear juice (A1), common pear juice (A2), and hybrid juice (A3). These measures were used to summarize the central tendency and variability in the concentrations of Ca, Mg, K and VIT C across the samples. The mean values provided an estimate of the average nutrient content for each formulation, while the standard deviations indicated the degree of variation within the data. This descriptive statistical approach facilitated a comparison of the nutrient profiles among the juices, identifying which formulation offered the highest nutrient density. The dietary contribution of each juice

formulation was compared to the Dietary Reference Intakes (DRIs) ranges for men and women. One-way analysis of variance (ANOVA) was performed to compare the significance of differences among means ($p < 0.05$).

3.5.3 Dietary Reference Intakes (DRIs) and Nutrient Density Index

To calculate the percentage of Daily Recommended Intake (DRI) per serving the following for each juice the equation was utilized (1):

$$\text{Percentage of Daily Recommended Intake (DRI) per serving} = \frac{\text{Mean}}{\text{DRI}} \times 100 \quad (1)$$

In this study, the Nutrient Density Index (NDI) was calculated by normalizing nutrient content to 100 kcal to ensure consistency and comparability across formulations, while actual juice measurements were standardized to a 250 mL serving size. The 100 kcal normalization is a widely used method in nutrient profiling, as it allows for the assessment of foods based on their nutrient richness relative to energy content, independent of serving size variations [54]. This approach aligns with global practices such as the Nutrient Rich Foods (NRF) Index and facilitates the identification of nutrient-dense products that support nutrient adequacy without contributing excessive caloric intake [55]. By integrating this method, the study highlights the nutritional contributions of the juice formulations in a manner applicable to dietary recommendations and public health strategies.

To calculate the Nutrient Density Index (NDI) for the three juice formulations (A1: Prickly Pear, A2: Common Pear, and A3: Hybrid) the study used the following equation (2):

$$NDI(\text{individual nutrient}) = \frac{\text{Nutrient Content (mg or } \mu\text{g)}}{\text{Energy content (kcal)}} \quad (2)$$

An overall NDI for all three juices that combines multiple nutrients, the following equation (3) was used to calculate:

$$\text{Composite NDI} = \frac{\sum \left(\frac{\text{Nutrient}_i}{\text{DRI}_i} \right)}{\text{Energy content (kcal)}} \quad (3)$$

Where:

- Nutrient_i is the content of each nutrient.
- DRIs is the Daily Recommended Intake for that nutrient.

This formula accounts for the relative contribution of each nutrient to the overall nutrient density of the juice.

4. Results and discussion

4.1 Nutritional Composition and Recommended Daily Allowance (RDA) per Serving of Juice Samples

The following tables provide a detailed analysis of the nutrient composition and dietary contributions of the three juice formulations (A1: Prickly Pear, A2: Pear, and A3: Hybrid). Table 1 presents the concentrations of calcium, magnesium, potassium, and vitamin C in each formulation, along with the respective recovery rates, measurement uncertainties, alignment with the Dietary Reference Intakes (DRIs) for individuals aged 51–70 years and ANOVA results (*p-values*). The *p-values* for each nutrient are 0.001, which is less than the significance level of 0.05. The results indicate that there are statistically significant differences in the concentration of each nutrient among the three-juice formulation.

Table 1: Nutritional content comparison of juice formulation.

Nutrient	Unit	LOQ	Recovery (%)	Uncertainty (%)	Mean \pm SD	DRIs (σ/φ)	<i>P-Value</i>
Calcium (Ca)	mg/100g	1	97	21	A1: 46.43 \pm 9.75 A2: 25.95 \pm 5.45 A3: 34.66 \pm 7.28	1200/1200 AI	0.001
Magnesium (Mg)	mg/100g	1	105	13	A1: 31.04 \pm 4.04 A2: 16.24 \pm 2.11 A3: 19.71 \pm 2.57	420/320 EAR	0.001
Potassium (K)	mg/100g	1	96	14	A1: 70.25 \pm 9.98 A2: 56.72 \pm 7.94 A3: 105.94 \pm 14.83	3600/ 2400 AI	0.001
Vitamin C (Ascorbic acid)	mg/kg	5	96	9	A1: 33.56 \pm 3.02 A2: 17.57 \pm 1.58 A3: 138.88 \pm 12.5	75/60 EAR	0.001

NB: 0.001 means statistically significance at 1%.

Table 2 summarizes the percentage contributions of each juice formulation to the daily DRIs for men and women. This table highlights the potential nutritional benefits of consuming these juices, particularly the hybrid juice (A3), which shows enhanced contributions to vitamin C and potassium intake relative to the other formulations.

Table 2: Percentage of Daily Recommended Intake (DRI) per serving.

Nutrient	Unit	A1 % DRI (♂M/♀F)	A2 % DRI (♂M/♀F)	A3 % DRI (♂M/♀F)
Calcium	Mg	3.87%	2.16%	2.89%
Magnesium	Mg	7.39% / 9.70%	3.86% / 5.08%	4.69% / 6.16%
Potassium	Mg	1.95% / 2.93%	1.58% / 2.36%	2.94% / 4.41%
Vitamin C	Mg	44.75% / 55.93%	23.43% / 29.28%	185.17% / 231.47%

Calcium Content

Among the formulations, prickly pear juice (A1) demonstrated the highest calcium content providing 46.43 mg/100g, which translates to 3.87% of the daily Adequate Intake (AI) of 1,200 mg. These findings align with the findings of [56] who also found that prickly pear had the highest calcium content. The hybrid juice (A3) followed with 34.66 mg/100g (2.89%), while pear juice (A2) provided the lowest calcium content at 25.95 mg/100g (2.16%). Although the calcium contributions from these juices are modest compared to the daily AI, their inclusion in the diet can complement other sources, especially in populations with limited access to dairy products. Furthermore, if A1 and A3 are to be consumed using a normal 250ml standard glass serving a higher nutrient contribution could be derived from these juices for a single serving. Calcium is essential for maintaining bone density and preventing osteoporosis, a common concern for ageing individuals [57, 58]. Accessibility of calcium-rich yet affordable foods could be an advantage for menopausal women particularly those who are living in rural communities, who often have less intake of dairy products [59]. The differences are attributable to the natural calcium content of prickly pear, which is known for its mineral density. Since calcium is essential for bone health and cellular function, A1 stands out as a potentially significant source of calcium in rural diets where calcium deficiency is prevalent. The hybrid formulation A3 also shows promise by offering a balance between calcium density and palatability.

Magnesium Content

For magnesium, prickly pear juice (A1) again emerged as the most nutrient-dense option, offering 31.04 mg/100g, equivalent to 7.39% of the EAR for men (420 mg/day) and 9.70% for women (320 mg/day). The hybrid juice (A3) provided 19.71 mg/100g, contributing 4.69% and 6.16% of the EAR for men and women, respectively. Pear juice (A2) had the lowest magnesium levels, with 16.24 mg/100g, meeting 3.86% of the EAR for men and 5.08% for women as shown in Table 2. Extensive research by other scholars has shown that magnesium is critical for energy metabolism, muscle function, and nerve [40, 59, 60]. Nutrients such as sub-Saharan farmers report magnesium to be limited in access for bio-fortification during cereal production to assist micronutrient deficiencies in communities therefore, forest fruit can be an alternative source [61]. These findings highlight the potential of prickly pear and hybrid juices to address magnesium deficiencies, particularly in undernourished populations. This result is not surprising as prickly pear is known for its rich mineral profile, particularly magnesium, which is critical for metabolic functions and maintaining muscle and nerve function [40, 59]. Despite its lower content, the combination formulation still offers a more balanced contribution compared to pear alone.

Potassium Content

Table 2 shows the percentage of the Daily Recommended Intake (DRI) for potassium provided by each juice formulation. For juice A1, it contributes 1.95% of the DRI for men (3600 AI) and 2.93% for women (2400 AI). Juice A2 offers a slightly lower contribution, providing 1.58% for men and 2.36% for women. In contrast, juice A3 provides the highest percentage of potassium, delivering 2.94% of the DRI for men and 4.41% for women. This makes A3 the most significant source of potassium among the three formulations, with a notably higher contribution, especially for women. Therefore, A3 stands out as the best option for increasing potassium intake compared to A1 and A2. Potassium is crucial for maintaining fluid balance, supporting cardiovascular health, and regulating blood pressure [62]. The enhanced potassium content in the hybrid juice reflects a synergistic effect, likely resulting from the combination of prickly pear and pear, making it particularly valuable for improving heart health in ageing populations. The hybrid formulation demonstrates the synergistic effect of

combining the two fruits, resulting in a higher potassium content. This could make the combination juice an excellent dietary option for individuals aiming to maintain healthy blood pressure levels.

Vitamin C Content

Vitamin C content showed the most dramatic differences among the juices, with the hybrid juice (A3) containing an impressive 138.88 mg/kg, meeting 185.17% of the EAR for men (75 mg/day) and 231.47% for women (60 mg/day). Prickly pear juice (A1) provided 33.56 mg/kg, meeting 44.75% and 55.93% of the EAR for men and women, respectively, while pear juice (A2) contained only 17.57 mg/kg, contributing 23.43% for men and 29.28% for women. The hybrid juice's exceptional vitamin C density underscores its potential as a potent antioxidant source, supporting immune health, collagen synthesis, and protection against oxidative stress [27, 63]. This makes it particularly beneficial for individuals at higher risk of nutrient deficiencies due to limited dietary diversity. The combination juice provides an impressive boost in vitamin C content, likely due to the complementary effects of both fruits. This result highlights the potential health benefits of consuming the hybrid juice, particularly for boosting immune function. Moreover, vitamin C good quality sources such as oranges are usually seasonally available in winter months hence, the availability of *Opuntia ficus-indica L.* in a different season can be beneficial as an alternative [27].

The findings of this study contribute to growing evidence supporting the integration of underutilized indigenous fruits like prickly pear into mainstream food systems. The hybrid juice formulation offers a practical solution to malnutrition by combining the nutrient density using fruit as a forest resource. This aligns with research emphasizing the need for diversified diets as a strategy to combat food insecurity in rural areas [64]. The high nutrient density of A3 positions it as a functional beverage that can be introduced into school feeding programs, community nutrition initiatives, and healthcare settings. The ability to deliver a concentrated source of essential vitamins and minerals cost-effectively can significantly impact public health, particularly in resource-constrained environments.

3.2 Nutrient Density Index (NDI)

Table 3 shows the Nutrient Density Index (NDI) which highlights the relative nutrient content per calorie for the three juice formulations. Among the formulations, prickly pear juice (A1) consistently emerges as the most nutrient-dense in calcium and magnesium, with NDIs of 0.4643 mg/kcal and 0.3104 mg/kcal, respectively. These results affirm the robust nutrient profile of prickly pear, making it a valuable dietary option in resource-limited settings [7, 13, 19, 24]. Its high calcium content supports bone health [58], while magnesium is essential for energy metabolism and muscle function, aligning with literature that emphasizes the prickly pear's dense mineral composition [60].

Table 3: Measured Nutrient Density Index (NDI) per juice variety.

Nutrient (per 100g)	A1 (Prickly Pear)	A2 (Pear)	A3 (Hybrid)
Calcium (mg)	0.4643 mg/kcal	0.2595 mg/kcal	0.3466 mg/kcal
Magnesium (mg)	0.3104 mg/kcal	0.1624 mg/kcal	0.1971 mg/kcal
Potassium (mg)	0.7025 mg/kcal	0.5672 mg/kcal	1.0594 mg/kcal
Vitamin C (mg)	0.3356 mg/kcal	0.1757 mg/kcal	1.3888 mg/kcal
Composite NDI	0.4532 mg/kcal	0.2912 mg/kcal	0.7480 mg/kcal

In contrast, the hybrid juice (A3) demonstrates the highest nutrient density for potassium and vitamin C, with NDIs of 1.0594 mg/kcal and 1.3888 mg/kcal, respectively. This synergistic enhancement underscores the benefits of combining prickly pear and common pear, yielding a product that optimally supports improved nutrition due to the evidence of its contribution to cardiovascular health and immune function [24, 29]. The hybrid formulation represents an innovative approach to enhancing nutrient intake, leveraging the complementary strengths of the individual fruits. The common pear juice (A2), while lower in nutrient density across all metrics, provides a baseline for comparison and highlights the improvements gained through hybridization. NDIs reflected varying values from 0.2595 mg/kcal for (calcium), 0.1624 mg/kcal (magnesium), 0.5672 mg/kcal (potassium), and 0.1757 mg/kcal (vitamin C).

The composite NDI, calculated as the average of individual nutrient densities, reveals the overall nutrient efficiency of each formulation. Prickly pear juice (A1) scores a composite NDI of 0.4532, emphasizing its broad-spectrum nutritional value. The common pear juice (A2) has

a lower composite NDI of 0.2912, reflecting its comparatively limited nutrient density. The hybrid juice (A3) achieves the highest composite NDI at 0.7480, illustrating its enhanced nutritional profile and potential as a functional beverage for addressing nutrient deficiencies. Nutritional benefits derived from this forest resource demonstrated the relevance of how such fruits not only offer nutrient density but also enhance agro-biodiversity, since this fruit is also considered an ornamental plant and should be prioritized for sustainable impact [20].

This comparative study has shown possible nutrient profiling per selected fruit and the combination of fruits usually accessible in local markets. The study has underscored the existing reality that indigenous food and the loss of their maximum utilization is imperilled by many factors such as colonial influence and markets that have more advantage on fruits such as common pears as opposed to *Opuntia ficus-indica* L. The option of developing A3 highlights the potential of using hybrid formulation as a method. The results hold significant implications for rural communities, where malnutrition and food insecurity are prevalent. The hybrid juice offers a cost-effective, nutrient-rich solution that can be locally produced, making it accessible to vulnerable populations. The integration of prickly pear, a hardy, drought-tolerant species, into local food systems aligns with the environmental conditions of many rural areas, enhancing the resilience of agricultural practices. According to [65] Prickly pear is a good source of natural antioxidants, hence it can be used in a range of other food product formulations, as nutritional supplements. Furthermore, the use of hybrid products creates opportunities for income generation through small-scale processing and local markets, contributing to the economic empowerment of rural households that are under-resourced. Research in South Africa has also shown the increasing demand for this fruit and other cultivars are being explored, since they can benefit commercial markets and also be used for animal feed [57].

5. Conclusions

The preservation of forest resources particularly such as *Opuntia ficus-indica* L. is vital in its contribution to food and nutrition security and as a future food that could be explored to address some of the nutritional gaps. The lack of continuous integration and the promotion of *Opuntia ficus-indica* L. within farming communities reveals a gap that exists in how the value of forest fruits can contribute towards nutrition and sustainability. The benefits of

Opuntia ficus-indica L. had existed for this community however, this paper aimed to scientifically expose the nutritional benefits that exist with an objective to engage the community with the formulated products for further utilization. This study evaluated the integration of *Opuntia ficus-indica* L. (prickly pear) and *Pyrus communis* (common pear) to assess their potential to address malnutrition and promote sustainable food systems in rural communities.

The combination of these two fruits in a hybrid product has the potential to enhance both food security and economic opportunities in rural areas. The research has explored the possibility of integrating food sovereignty in rural communities using forest fruit with commercially available fruit to show a significant relationship. The unique and complementary strengths of these fruits were used to create a product offering for vulnerable communities. These juices could offer a balance of flavour, accessibility, and nutritional value, making it a suitable product for rural communities looking to diversify their food options while preserving local biodiversity. By creating a product that integrates the strengths of both fruits, this study demonstrated the potential for developing hybrid food products that can address malnutrition, promote sustainable agriculture, and contribute to food security in rural areas of the South Coast Region of KwaZulu Natal.

The ecological and agricultural benefits further underscore the value of these fruits. The prickly pear's ability to thrive in arid and degraded lands makes it a vital resource for promoting biodiversity and soil rehabilitation, while the common pear's established market appeal ensures broader acceptance and commercialization potential. Together, they provide a pathway to diversify diets, improve food security, and foster economic resilience in resource-constrained settings. Despite its promising findings, the study acknowledges limitations, including the small-scale experimental setup. This restricts the direct applicability of results to broader contexts, necessitating further research at larger scales to confirm the scalability, economic feasibility, and long-term health impacts of hybrid products. Moreover, while the hybrid formulation shows great potential, its acceptance and adaptability in different regions remain areas for exploration. By bridging nutritional gaps, improving livelihoods, and enhancing ecological sustainability, the findings of this study demonstrate a practical, scalable, and impactful approach to addressing the multifaceted challenges faced by rural communities. This research contributes to the growing discourse on sustainable nutrition,

offering a model for integrating underutilized resources into mainstream food systems which support the global sustainability agenda. It has further corroborated the viewpoints that exist on the relevance of indigenous forest fruits as valuable resources and the need to integrate them into existing farming systems. The comparative analysis using indigenous crop value-adding through the processing of *Opuntia ficus-indica* L. was an untapped reality for this study area. The significance of these research findings has further demonstrated how agrobiodiversity supports nutrition by offering nutrient-dense options and strengthening local food systems for future generations.

6. Recommendations for future research

This research has revealed a need to develop potential avenues targeted towards rural development on knowledge transfer through local chiefs, farmers, and community members. Rural communities should have tailor-made agricultural and nutrition programmes that deal with the preservation and benefits *Opuntia ficus-indica* L. including other forest fruits. Promoting the cultivation of prickly pear and common pear through incentives and integrating their use into agroforestry systems can increase their accessibility and sustainability.

Post-harvest handling and agro-processing technologies should be developed for capacity building to further extend the usage of this fruit. Furthermore, technologies to harvest the fruit should be developed by the community since some are often left hanging and get rotten which amounts to food waste. However, only highly skilled, and contrastive collaborations should be formulated to avoid overharvesting and the depletion of this fruit. In addition to providing technologies, upgrading infrastructure to support local production and cold storage, as well as leveraging renewable energy for processing and transportation, could further reduce environmental and financial costs. These measures will ensure that indigenous and commercial fruit integration becomes a sustainable and impactful approach to addressing nutritional and ecological challenges.

Market development initiatives, coupled with farmer training on sustainable harvesting and hybrid product formulation, are critical for ensuring economic viability. Further research should explore the long-term health impacts and broader market potential of hybrid products, particularly in rural and semi-arid regions.

Author contribution

Xolile Mkhize: Product Conceptualization, Investigation, Visualization, Study Design, Writing - original draft & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Validation and Supervision. **Thobani Cele:** Writing original draft– review & editing, Methodology, Software, Formal analysis, Data curation and Validation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. This work is original, and artificial intelligence was not used to formulate it.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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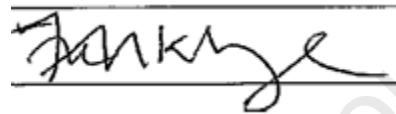
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Thank you