Material Flow Analysis and Resource Recovery Potential Analysis of Selected Fruit, Vegetable and Nut Waste in Kenya

Steven De Meester (steven.demeester@ugent.be)
Ghent University: Universiteit Gent https://orcid.org/0000-0002-5246-3918
Benson Dulo
University of Ghent: Universiteit Gent https://orcid.org/0000-0002-4815-4469
John Githaiga
Moi University School of Engineering https://orcid.org/0000-0002-4172-4756
Katleen Raes
Ghent University: Universiteit Gent

Research Article

Keywords: Kenyan bio-waste, valorisation, banana, coconut, potato, Material Flow Analysis

Posted Date: September 20th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-886139/v1

Abstract

In Kenya, agriculture is an important economic activity, which implies that a significant amount of bio-waste is generated. This is on one hand a waste management problem, but on the other hand, it is an opportunity for creating a sustainable bioeconomy. Therefore, this study investigates the potential recovery of bioresources from Kenyan bio-waste. The study first quantifies occurrence, current usage and disposal of three selected biomass types, being banana, potato and coconut waste. Next, material flow analysis (MFA) is used to systematically track the mass flow of these wastes. Finally, the potential of biomolecules, biomaterials and bioenergy from the waste streams is evaluated. The study revealed that 6007, 426 and 49.5 kt of banana, potato and coconut biomass is wasted. All these wastes can be biorefined, offering potential towards recovery of; flavonoids (88.3 kt), starch (377 kt), cellulose (2000.7 kt) and biogas (1757.0 GWh), being the total potential of the main bioresources from the three waste streams. The study therefore, concluded that, with proper waste collection, sorting and valorisation, there is a huge potential for bioeconomy in Kenya, at the same time reducing waste management problems.

Statement Of Novelty

Resource recovery potential analysis is performed on Kenyan fruits, vegetable and nut wastes. With proper waste collection, sorting and valorisation, there is a huge potential for improved bioeconomy in Kenya and similarly to many other (developing) countries, at the same time reducing waste management problems. In Kenya, and in broader sense, many developing countries, where agriculture is a key economic activity, implying that a significant amount of bio-waste is generated, there is no waste mapping or systematic study due to lack of data collected on the agricultural and food waste generation and destination. Limited literature that exist, however, show that the wastes are generally not valorized, despite the potential of recovering a high value bioresource from the waste streams. The paper also evaluates the logistics of the bioresource recovery.

Introduction

In the year 2019, around 8 million tons of solid waste was generated in Kenya and the rate of generation is likely to double by the year 2030, driven by socio-economic development and rapid population growth [1]. Between 2009 and 2019, the country's population increased by an average of 1 million people annually, while at the same time, Kenya achieved a middle-level income status, which resulted into an increasing demand for food and other resources [2]. Further, this implies that a significant amount of bio-waste is generated. To alleviate these challenges, efforts should focus on resource efficiency and circular economy. This would imply that resources are used efficiently throughout all stages of their lifecycle and throughout the supply chain, by emphasizing minimizing waste or transforming them into high quality secondary raw materials [3–5].

In Kenya, and similarly to many other (developing) countries, these bio-wastes are often burned or disposed of in open landfills, directly leading to environmental pollution and to climate change through particulate and greenhouse gas (GHG) emissions. Furthermore, due to prevalent tropical climate, the pile of bio-waste often becomes a habitat to pests and rodents and hence becomes a nuisance with corresponding health implications [6].

Since agriculture is the main economic activity in Kenya, contributing directly and indirectly to over 50% of the country's gross domestic product (GDP) and providing livelihoods to over 80% of the entire population, the sector is expected to generate high quantity of bio-wastes [7]. Indeed, according to research conducted in Kenya, organic wastes from urban markets alone (excluding waste or inedible parts that remains at the farm gate and collection centers), forms over 4,000 kt representing over 50% of all wastes produced in the urban centers per year [8]. However, despite the high quantity of these types of waste and their related environmental and health hazards, the rate of valorization is just about 40 kt accounting for about 1% of the total urban organic waste alone per year, thus, bio-wastes is a key contributor to waste management problem in Kenya [8, 1, 6]. This can be ascribed to the dispersity of waste generation, but also, there seems to be little knowledge about the potential benefits of waste valorization. In cases where these wastes are utilized, they are turned into relatively low added value products such as mulch, compost, energy (by burning) or in best case scenario, as animals feed [8, 9].

At a policy level, Kenya adopted the "Transforming our world: the 2030 Agenda for Sustainable Development", which aims to make the human environment safe, resilient and sustainable, ensuring sustainable production and consumption patterns and also reducing GHG emission by 30% by 2030 under the United Nation (UN) Framework Convention on Climate Change [1]. Strategic decisions now have to be made on how to achieve these targets. Science could support interventions towards an effective conversion of wastes from the food chain to usable, preferably high-valued products.

As a starting point for policy implementation in this context, mapping of the situation of these wastes should be performed, including current quantities, origin and destinations. One of the tools that can be used for this purpose is Material Flow Analysis (MFA). Indeed, MFA has been used for the analysis of organic waste flow in amongst others, Europe [10], UK [11], US [12], Asia [13] and proven to be useful in the support of organic waste management and recycling policies by allowing visualization and quantification of flows that are to be managed. Nevertheless, agricultural and food waste generation and destination in Kenya, and in broader sense, many developing countries still lacks mapping as there is no systematically collected data. There is, however, a bit of unpublished literature, sometimes in local languages, and some other local information which is generally not accessible to a broad audience [14].

Within this specific Kenyan context, the main objective of this research is to study the potential of bioresource material recovery from selected Kenyan agricultural-based waste. This paper identifies quantity, occurrence, current usage and disposal trends of the most important fruit, vegetable and nut waste streams in Kenya. The information is summarized in a comprehensive MFA, to track the mass flow of selected waste streams from production through processing, consumption and disposal. Finally, the potential bioresource materials recoverable from the waste streams and the logistics of recovery are evaluated.

1.1 Preface: selection of case study

Within this study, a broad inventory of fruit, vegetable and nut wastes quantities in Kenya was made that informed the selection of different case studies for the valorization potential of the waste streams. Apart from the waste quantities, the case studies were also selected based on their inherent differences, including, dry versus wet waste, soil grown vis-a-vis above ground (tree) based wastes. Table 1 gives an overview of top ten fruit, vegetable and nut wastes in Kenya. Based on this inventory, we selected banana, potato and coconut waste as case studies, for each of these groups. In Table 1, the potential quantity of waste (column 7) is derived from the production quantity (column 5) and the potential waste proportion (column 6) found in literature.

Table 1
Top ten fruits, vegetable, and nuts in in Kenya in the year 2018

Product class	Production Rank	Agricultural product	Nature of waste	Production in $Kenya_{FW}$ (kt)[15]	Approximate potential waste (%)	Derived potential quantities of waste (kt) $_{FM}$
Fruits	1	Bananas (plantain, dessert and other)[a]	Pseudostem, peel, stock, leaves, bud, rotten pulp	1447	88[e,f]	1273
	2	Mangoes, Mangosten, Guavas[a]	Pomace, peel, stone/seed, seed coat	676	47[f]	318
	3	Tomato[a]	Pomace, cull tomato	599	20[g]	120
	4	Pinneaples[a]	Pomace, peel, crown	349	46[f]	161
	5	Avocado[a]	Pomace, peel, stone, seed coat	234	26[f]	61
	6	Water melon[a]	Peel, seed/rind	189	48[f]	91
	7	Papaya[a]	Pomace, Peel, seed	134	47[f]	63
	8	Fruit citrus nes[a]	Pomace, peel, seed	84	34[f]	29
	9	Oranges[a]	Pomace, peel, seed	72	24[f]	17
	10	Fruit tropical fresh nes[a]	Peel, seed/stone, rind, skin, pomace	39	27[f]	11
Vegetable	1	Irish Potatoes[b]	Peel	1870	16[f]	299
	2	Cassava[b]	Peel	946	28[h]	265
	3	Sweet potatoes[b]	Peel	871	22[f]	192
	4	Beans, dry[c]	Hull, germ powder, husk, Broken grain	837	18[g]	151
	5	Cabbages and other brassicas[a]	Trim losses	674	20[f]	135
	6	Vegetables, fresh nes[a]	Trim losses	670	20[f]	134
	7	Spinach[a]	Trim losses	169	20[f]	34
	8	Pigeon peas[c]	Hull, germ powder, husk, Broken grain	86	40[g]	34
	9	Onions, dry[b]	Outer leaves, tunic, basal plate, roots	35	11[f]	4
	10	Beans green[c]	Pods	34	n.d	-
Nut	1	Coconuts[c]	Shell, husk	105	47[i]	49
	2	Macadamia (nut nes)[c]	Shell	27	40-45j	11
	3	Groundnuts[d]	Shell, karnel	21	25[j]	5
	4	Cashew nuts[c]	Shell	14	55-65[j]	8
	5	Bambara nut	Shell	3.4		
	6	Areca nuts[c]	Shell, husk	0.1	60-80[j]	0.7
	7	Nutmeg, mace and cardamoms[c]	Shell, seed	0.06	-	-
	8	Chestnut[c]	Shell	n.d	25[k]	-
	9	Walnut[c]	kernel, green husk, shell	n.d	67[l]	-
	10	Hazel nut[c]	Shell	n.d	67[i]	-

[a] Wet, on ground waste (tree), [b] Wet, underground waste, [c] dry on ground waste, [d] dry underground waste, e [16], [f] [17], [g] [18] h [19], [l] [20], [j] [15], [k] [21], [i] [22], n.d: not determined

Banana is a herbaceous plant in the genus *Musa* and family Musaceae and is cultivated mainly for its fruit [23]. Banana plants consist of a rhizome (corm), a succulent stem called pseudostem, leaves, and a stock (rachis or peduncle) which supports an oval inflorescence consisting of deep purple waxy bracts (male bud) enclosing the female and male flowers in the lower and upper rows respectively. The female flowers eventually develop into banana fruits (hand). The fruits are harvested after every four to six months of planting [24] and are normally covered by a thick skin (peel) which is peeled off to expose the edible part (pulp). Except for the pulps and sometimes the rhizomes, all parts of the banana plant are potential waste [23]. These potential by-products are about 88% of the whole banana plant [16] which translate to an estimated 0.22 kt of waste per hectare in countries such as India, where the average yield of banana is about 30 t per hectare [25].

In Kenya, banana is the most important fruit in terms of productivity and is available throughout the year. For example, in 2017, banana fruits accounted for about 14.5% of the total value of horticulture and 35.9% of all fruits produced [26]. Typically, there are two cultivars of bananas in Kenya namely the desert (*Musa sapientum*) - the ripe edible cultivar and the plantain (*Musa paradisiaca*) - the cooking cultivars [27]. The two cultivars generally have similar morphology and are generalized as bananas [27] and will be considered so in this study.

Irish potato (*Solanum tuberosum L.*), is a root vegetable in the family of Solanaceae and genus *Solanum*. Due to its high nutritional value and adaptability to different climates, Irish potato tuber is the second most important staple food and strategic security crop in Kenya after maize and accounts for about 50% by volume of all vegetables produced and approximately 23.5% by value of the horticultural produce [28, 29]. It is grown by around 800,000 farmers who retain around 10% of their produce as seed potato and sell the rest mainly at local markets [30, 31]. Annually, about 1.5 to 2 million tonnes of potatoes are produced mostly by a few large-scale farmers and many small-scale farmers [32, 29]. Irish potato plants consist of stems, branches, leaflets, roots, auxiliary buds, flowers and an enlarged portion of the stolon called tubers. Maturity is characterized by dehauliming, senescence or vine desiccation involving stem, branches and leaves yellowing or turning brownish and eventually drying and dropping off or being mechanically removed to allow tuber skin to harden and reduce damage to the tubers during harvesting [33, 29]. The main part that remains after desiccation is the tuber, of which during harvesting and subsequent processing, generates rotten/rejected tubers and peels as the main potential wastes comprising about 25% and 12% of the total potato production respectively [32, 34].

Apart from farm gate production wastes for both bananas and Irish potatoes, further wastes is generated during transportation, packaging, storage, sales and consumption due to, among other factors, adverse weather effects such as temperatures, poor road networks etc.) [35]. Furthermore, rejects are created due to attacks by pests and diseases, damage or inefficiencies during harvesting and processing, or as a result of over-supply and competition [27, 35, 36].

Cocos nucifera L. is a palm tree that belongs to the family Arecaceae and genus *Cocos.* The coconut palm tree produces a nut referred to as 'coconut' and is the highest productive nut in Kenya and accounted for over 58% of productivity of all nuts in 2018 [15]. In the same year approximately 10 million coconut trees with over 277 million nuts made up the Kenyan coconut industry of which 95% are in the costal belt [37, 38]. The Coconut tree consists of roots, trunk, fonds or leaves, flowers and the nuts which are commercially exploitable. The roots can be used as dye stuff and for medicinal purposes but are often left in the field as dry stocks to be used for firewood; trunks are used for; fuel, making furniture, building huts and other physical structures, canoe building, coffin making and performing important cultural practices such as crafting of grave posts (*kigango*) [39]. Fonds, such as fallen, dry or used coconut leaves *(kanja)* are used mainly as roof thatching material (*makuti*) for both the local houses and exotic tourist hotels and also for stuffing pillows and mattresses, making brooms, weaving mats (*mkeka*) and fish traps, while sap from inflorescence (fruit bud), stem or root can be tapped to produce toddy *(mnazi)* which is fermented to produce an alcoholic drink (palm wine) [40, 39, 38, 41]. The nuts are nutritious and are consumed at a tender stage (*madafu*) and at their mature stage in form of copra oils, copra cake, hence, the coconut trees are thus useful as cash crop due to their multi-purpose uses [42, 43]. The processing of coconut generates shell and husk as the main by-products and constitutes about 12% and 35 % of the whole fruit by weight respectively [20]. Also, coconut cake meal is produced as a by-product of copra processing but due to its nutritional value, it is being used in confectionery [44].

For these 3 case studies of banana, Irish potatoes and coconut, a Material Flow Analysis in Kenya context was performed.

Methodology

2.1 Material Flow Analysis

MFA is a methodology that allows systematic analysis and quantification of flows and stocks of material or substances in a well-defined system in space and time. It analyses material sources, pathways and final destinations according to the mass balance principle i.e. the sum of all inputs equals the sum of all outputs, corrected with stock change if any. In this study, MFA is used to point out the potential for the valorization of three (3) selected types of biomass. Based on data availability, the MFA evaluate production quantities from the year 2018. Flow calculations were performed in Microsoft Excel, while the Sankey 5 pro software (version e! Sankey pro 5.1.0) was used to develop the MFA flow diagrams. The subsequent section present essential information on system description, data used, and assumptions made.

2.2 System boundary description

The spatial border of Kenya defines the system boundary, implying that only waste generated within this spatial boundary will be considered in this study i.e., wastes related to import or export are excluded from this study. The temporal boundary was the year 2018. Furthermore, throughout the study, the term “waste” refers to a secondary product derived from agricultural production, supply, agro-industrial processing and consumption of the selected agro-products. This normally includes biomass that is inedible to humans, including food or by-products that are edible but are degraded beyond consumption or processing [45]. We follow waste generated over the production chain of the fruits, vegetables and nuts, including harvesting, processing, trading, consumption and final waste residual treatment. However, some potential wastes are not included in the study, for example, potato flowers, stem, branches and leaves dry out and drops before harvesting. Also, the banana rhizome is excluded from the study, since the new bud and suckers normally sprout from it [43]. Coconut roots, trunk and leaves are already extensively used thus are not considered as wastes in this study. To facilitate the usage of MFA, a generic scheme is developed (Fig. 1) that was used to assess the occurrence of the wastes. The functional unit is the total quantity of produce in 2018, being 1447 kt for bananas, 1870 kt for potatoes and 105 kt for coconut.

Figure 1 considers all parts of the banana plant except the rhizome. It also considers potato tubers and husked coconut and their associated processing wastes. All of the three case studies generate wastes at the farm gate (lines 2 and 3). However, those from coconut such as husks are separated by retting or decortication process (line 9 and 10) before they are finally processed and/or disposed of. Also, there are potato and banana rejects at the post-harvest (preparation, storage and distribution) (line 6), retailing (line 12) and consumption (line 13) stage. However, the quantity of banana rejected at post-harvest and retail stages is insignificant thus have not been considered, likewise to quantity of coconut used as seeds. Reused material waste are wastes that are generated after an initial use of a by-product or waste.

2.3 Data source and assumptions

In this study, mainly literature data was used. Production data for 2018 was sourced from FAOSTAT 2019 since it was the most recent source for which all required data on production were available for Kenya. Other available local data were used whenever possible. For the case of banana waste proportion and use, credible local data was not available, hence data was obtained from research conducted within the region of East and Central Africa and transposed to the Kenyan context. Waste was quantified in both dry and wet mass. The data on some potential key material resources in each by-product considered are given in Table 2.

Table 2
Production and waste quantity data sources

Flow no.	Process in supply chain	Banana	Potato	Coconut
1	Farm production (product)	[15]	[15]	[15]
2,3	Farm production (waste)	[46, 36], calculated from assumption[a]	[47]	[20]
4	Planting (Seeds)	n.a	[31]	n.a
5	Preparation, storage and distribution (product)	[46, 36]	[48, 47]	[20]
6	Preparation, storage and distribution (waste)	Negligible[b]	[47]	n.a
7, 8	Factory processing, retailing (product)	[46]	[47]	[49]
9, 10	Retting process (waste)	n.a	n.a	[20]
11,12	Factory processing and retailing (waste)	[27]	[47]	[49]
13	House hold and restaurant consumer (waste)	Neglegible[b]	[47]	[49]
14	Banana food pulp, potato tuber for food and coconut based food	Calculated[i]	Calculated[i]	Calculated[i]
15, 16	Consumed, secondary (waste)	[50]	[48]	[49]
17,18	Discarded materials (waste)	Calculated[i]	Calculated[i]	Calculated[i]

[a] Based on an assumption that each bunch of 30.5 kg banana fruit has 0.5 kg male bud, [b] Based on an assumption that the quantity is unimportant since damaged fruits are sold as low quality products [27] and that household consumers and restaurants do not store their purchases, [i] based on mass balance, n.a: not applicable.

In this work, quantity determinations were subjected to certain assumptions. The most important assumptions are:

i. All produce from each of the selected case studies strictly follow the supply chain as shown in Fig. 1.
ii. There is no significant difference in yield, morphology and phytochemical constituents among different varieties in each of the case studies, hence, an average value is adopted.
iii. Due to lack of data and for simplicity, imports and exports were not included.

2.4 Recoverable bioresource classification

The potential recovery of essential material from these wastes is discussed in the context of Kenyan need. A literature search was done on the concentrations of recoverable components and bioenergy potential. We classified recovery routes into four groups: high value compounds (e.g. phenolic materials), extractable (macro)compounds for use in feed and food (such as protein, starch and sugar), macrocompounds to be used as technical materials for industrial applications (such as fibers, cellulose and lignin), and bioenergy potential (such as biogas and bioethanol potential). The groups are as shown in Fig. 2.

Result And Discussion

3.1 Quantity and occurrence

Table 3 shows bananas, potatoes and coconut production and waste quantities, their current use and final disposal trends while **Fig. 3**, show their respective material flows. From Table 3 it can be deduced that, on fresh weight basis, 6007 kt or 89.2 % of total banana tree by-products is potential waste. Out of the total waste, pseudostem waste stream accounts for 72.2% of the wastes, followed by leaves (11.6%), peels (10.6%), stock (3.9%), pulp (1.3%) and male bud (0.4%). As seen in **Fig. 3 (a)**, a significant quantity of banana wastes (4359 kt) representing about 72.6% of the total wastes is discarded to nature (i.e. either disposed of in open landfills or water bodies, left to rot or burned without energy recovery). The rest of the wastes (1648 kt or about 27.4 %) are used as animal feed (649 kt) and as soil improver (999 kt)). However, soil improvement activities such as mulching are discouraged due to possibility of the propagation of diseases such as banana bacterial wilt [36].

In case of potato, for the total tuber produced, 1257 kt (67.2%) is edible human food, 187 kt (10%) is retained as planting seeds, while about 426 kt (22.8%) are by-products in the form of peel (239 kt) and rejected tuber (187 kt). Further, the MFA analysis shown in **Fig. 3 (b)**, depicts that just like in the case of banana, potato by-products are currently used as animal feed (136 kt) and for soil improvement (60 kt), representing 31.9% and 14.1% of the total by-products respectively, while 230 kt representing about 54% of all potato wastes are discarded to nature.

For coconut, The Sankey diagram for coconut is shown in **Fig. 3 (c).** It shows that 49.5 kt or 47.0% of the entire coconut produced is potential waste, consisting of 12.6 kt shell (25.5%), 25.8 kt dust or pith (52.1%), 11.1 kt fiber (22.4%). Also, from the diagram, only 459 t (3.6%) of the shell is usable either for making charcoal (456 t) or artifacts (3 t), while about 12.2kt (96.4%) is discarded to nature. A combined 0.2% of fiber is used for making brooms (4 t), ropes (9 t) and mats/mattresses (4 t), while (11,046 t) 99.8% of the fibers, especially short fibers, is discarded. So far, pith or dust or cocopeat is only used as soil improver or as plant growing medium at about 2,078 t (8.0%), while a significant proportion 23,736 t (92.0%) is discarded in open land fill, thus, lost. In total, about 2,534 t (5.2%) of coconut wastes are consumed while 46,966 t (94.8%) is either discarded to nature whereas 20 t, is generated as a secondary waste source.

Comparably, on the basis of their respective total wastes, the highest percentage of materials discarded to open land fill occur in banana at 4359 kt (94%) followed by potato at 230 kt (5.0 %) and coconut at about 47 kt (1.0%). However, it is remarkable that where the wastes are used, so far, it is limited to animal feed and soil improvement, next to some very specific applications such as ropes and toys.

Table 3
Quantity of waste generated in Kenya and current destinations

Biomass	Nature of Waste$_{FM}$	Waste/ kt of fruit (kt/kt)	Produce/waste quantity$_{FM}$ (kt)	Food (kt)	Feed (kt)	Compost (kt)	Mulch (kt)	Rope making (kt)	Wrapping (kt)	Construction (kt)	Play/Toy (kt)	D (…
Banana	Fruit produced	1.000	1447									
	Peels	0.440[a]	637		185	449	0	0	0	0	0	3
	Pseudostem	3.000[a]	4341		174	109	260	1281	0	0	1302	1
	Stock	0.160[a]	232		10	119	0	1	0	0	39	6
	Leaves	0.480[a]	695		257	0	0	0	351	3	31	5
	Pulp	0.056[a]	81	729	23	58	0	0	0	0	0	0
	Male bud	0.016[b]	21	2	0	4	0	0	0	0	16	1
	Total waste	**4.152**	**6007**	**731**	**649**	**739**	**260**	**1282**	**351**	**3**	**1388**	**1**
	Tuber produced	1.000	1870									
Potato	Seed	0.100[c]	187	187								
	Peels	0.128[d]	239		76	34						1
	Pulp	0.100[d]	187	1257	60	26						1
	Total waste	**0.328**	**613**	**1444**	**136**	**60**						**2**
Coconut	**Nature of Waste**	**Waste (kt/kt) of nut)**	**Produce/waste quantity$_{FM}$ (kt)**	**Food (kt)**	**Feed**	**Charcoal (kt)**	**Artefact, cups (kaha) (kt)**	**Broom (kt)**	**Rope (kt)**	**Mat (kt)**	**Soil conditioner (kt)**	**D (…**
	Coconut produce	1.000	105.362									
	Food$_{FM}$	0.530[e]	55.842	55.842								
	Shell$_{DM}$	0.120[e]	12.643			0.456	0.003					1
	Fiber$_{DM}$	0.105[e]	11.063					0.004	0.009	0.004		1
	Dust$_{DM}$	0.245[e]	25.814								2.078	2
	Coconut Total	**0.47**	**49520**	**55.842**		**0.456**	**0.003**	**0.004**	**0.009**	**0.004**	**2.078**	**4**

[a] Kabege et al. and Fernandez et al. [46, 51], [b] From assumption no. 2, [c] GIZ [31], [d] Musita et al. [34], [e] Verma et. al [20].

3.2 Potential resource recovery analysis

This section discusses the potential recoveries of the four classes of biomaterials (see supplementary data) and are summarized in Table 4.

3.2.1 High value compounds

From Table 4, it is shown that, flavonoid can mainly be obtained from banana wastes, with banana peels having the highest potential at 34.9 kt, followed by pseudostem (33.9 kt), leaves (3.8 kt), stock (1.5), and bud (0.1 kt), all totaling to 74.2 kt flavonoids. Potato peels and mixed wastes have a potential to produce 0.4 kt flavonoids while there is less potential for these components in coconut waste. For tannin extract, the highest quantity can be extracted from banana peel (8.3 kt), coconut husk (1.8 kt), banana stock (0.9 kt), coconut shell (0.4 kt) and banana pulp (0.2 kt). In total, banana waste has a total potential to produce 9.4 kt tannin, coconut waste (2.2 kt), while potato wastes have less potential.

If these resources are tapped e.g. as a natural dye, flavonoids from banana wastes (74.2 kt) can be used to dye about 608 million m^2 of wool fabric (using dye to fabric ratio of 1:5 (w/w) [52] assuming wool fabric weight 610 g/m^2), tannin from coconut (2.2 kt) would be used to tan about 220 kt skin (at 1% (w/w) tanning process [53]).

3.2.2 Extractable (macro)compounds for use in feed and food

Banana waste has a high potential for refining extractable macro(compounds) that are usable as starting material for food and feed production processes (Table 4). In this category, starch is the main potential extractable material from banana waste streams (340.8 kt) with the highest quantities is recoverable from pseudostem (241.0 kt), followed by peel (71.2 kt), pulp (26.6 kt), leaves (1.2 kt) and stock (0.8 kt). From potato wastes streams, mixed waste and peels can generate 25.2 kt and 11.0 kt relatively while coconut has less potential. The potential for extractable sugar from pseudostem is 113.3 kt, leaves (6.5 kt), peel (2.1 kt), pulp and bud (1.4 kt) each. Each of the potato waste streams can produce 0.2 kt each of the extractable sugar, while only coconut husk has a potential to produce 13.7 kt of sugar. Banana pseudostem (31.0 kt), peel (13.4 kt), stock (5.9 kt), pulp (1.5 kt), leaves (1.5 kt) and bud (0.7 kt) have potential of producing protein.

Also, potato peel and mixed wastes streams each have a potential to produce 5.1 kt of protein. In total, the most promising extractable feed materials from banana wastes in terms of masses are starch (340.8 kt), followed by sugar (124.7 kt) then protein (54.0 kt). From potato waste, starch (36.2 kt) and protein (10.2 kt) are the most significant recoverable (macro)compounds for use in feed and food, while from coconut waste, sugar (13.7 kt) from the husk seems most promising.

The starch from banana (340.8 kt) and potato (36.2 kt) wastes can size about 2,272.0 kt and 241.3 kt cotton yarn (taking 15% of starch size per fiber (weight/weight) [54]) respectively; sugar from banana (124.7 kt) can produce 105 million liters ethanol, coconut (13.7 kt) can produce 11.5 million liters of ethanol (with the assumption that 1.6 g of sugar can produce 1.06 g ethanol [55]), while protein from banana 54.0 kt can be used as a food supplement to produce 540 kt spaghetti meal (at 10% protein supplement in spaghetti flour [56])

3.2.3 Macrocompounds used as technical materials for industrial applications

Technical fiber can be recovered from banana pseudostem (476.1 kt), stock (9.8 kt), leaves (2.8 kt) and coconut husk (11.1 kt) as shown in Table 4. For cellulose, the potential recoveries are banana pseudostem (1670.4 kt), leaves (247.3 kt), peel (23.3 kt), stock (15.3 kt) and bud (2.4 kt), potato mix (13.6 kt), potato peel (0.7 kt), coconut husk (19.2 kt), coconut shell (8.5 kt)

Table 4
Potential quantity of bioresource refinable from in banana waste streams

Biomass	High value compounds (kt)		Extractable (macro)compounds for use in feed and food (kt)			Macrocompounds used as technical materials for industrial applications (kt)			Bioenergy potential (GWh)	
	Flavonoid	Tannin	Starch	Protein	Sugar	Fiber	Cellulose	Lignin	Biogas* (GWh)	Bioethanol** (GWh)
Banana Peel	34.9	8.3	71.2	13.4	2.1	limited	23.3	24.9	305.4	34.4
Pseudostem	33.9	limited	241.0	31.0	113.3	476.1	1670.4	250.5	981.7	189.7
Stock	1.5	0.9	0.8	5.9	limited	9.8	15.3	9.2	70.7	26.8
Leaves	3.8	limited	1.2	1.5	6.5	2.8	247.3	73.5	91.6	28.8
Banana pulp	0.1	0.2	26.6	1.5	1.4	limited	limited	limited	69.0	19.2
Male bud	limited	limited	limited	0.7	1.4	limited	2.4	0.6	6.8	0.7
Potato peel	0.4	limited	11.0	5.1	0.2	limited	0.7	9.6	79.2	11.6
Potato mix	limited	limited	25.2	5.1	0.2	limited	13.6	2.8	77.4	34.4
Coconut shell	limited	0.4	limited	limited	limited	limited	8.5	3.9	56.0	limited
Coconut husk	limited	1.8	limited	limited	13.7	11.1	19.2	15.5	19.2	10.3

Limited – less than 0.1 kt, *calculated from 6.5 KWh per m³ biogas [57], **Calculated from the lower heating value (LHV) of 1 kg of EtOH (7.47 KWh/kg [58])

Table 5
Summary of the potential of biomaterial recovery from bio-wastes

Waste Parts	Moisture content	Dry matter (%)	$Quantity_{FM}$ (kt)	$Quantity_{DM}$ (t)	Occurance	Main Current destination	Potential future destination	Overal potential
Banana Peels	83.3[a]	28.0	637	178	Mainly dispersed	Compost, feeding	Flavonoid, starch, lignin, biogas	Medium
Pseudostem	90.0[b]	18.6	4341	807	Central	Play, rope, discarded (rotting/burned)	Flavonoid, starch, cellulose, biogas	High
Stock	90.5[a]	49.0	232	49	Central	Compost, discarded, play	Flavonoid, protein, cellulose, biogas	High
Leaves	80.0[b]	77.0	695	77	Central	Wrapping, feeding	Flavonoid, Sugar, cellulose, biogas	High
Banana Pulp	70.1[a]	41.0	81	33	Mainly dispersed	Compost, feeding	Tannin, starch, biogas	Medium
Male bud	87.5[b]	41.0	23	5	Central	Play	Sugar, cellulose, biogas	High
Potato peel	86.5[c]	23.0	239	48	Mainly dispersed	Discarded, feed	Flavonoid, starch, lignin, biogas	Medium
Potato mix	76.8[c]	20.2	187	55	Mainly dispersed	Discarded, feed	Starch, cellulose, biogas	Medium
Coconut shell	20[d]	n.a	13	13	Mainly dispersed	Discarded, soil improvement	Tannin, cellulose, biogas	Medium
Coconut husk	32[d]	n.a	37	37	Central	Discarded, soil improvement	Tannin, sugar, cellulose, biogas	High

[a] [36], [b] [59], [c] [60], [d] [61], Dry biomass of banana is 11,2 % [62], dry biomass of potato is 24.7 %, n.a – not applicable, central - located within one place, Mainly dispersed spread – small quantity is centrally generated (such as factory generated wastes) while large quantity is scattered in a wider area (such as retail and house hold generated wastes)

For lignin, the highest potential sources lies in pseudostem (250.5 kt), banana leaves (73.5 kt), banana peel (24.9 kt), coconut husk (15.5 kt), potato peel (9.6 kt), banana stock (9.2), coconut shell (3.9 kt), potato mix (2.8 kt) and bud (0.6 kt). Thus the total potential recovery for macrocompounds used as technical materials for industrial applications is: fiber from banana (488.7 kt) and coconut (11.1 kt); cellulose from banana (1958.7 kt), potato (14.3 kt) and coconut (27.7 kt); while from lignin from banana (358.7 kt), potato (12.4 kt) and coconut (19.4 kt)

The fiber from banana (488.7 kt) is capable of producing 1221.8 kt plain-woven banana fiber/polyester blend fabric or 2.4 million m^3 of fabric (assuming 40% banana fiber in hybrid polyester blend [63], banana fiber density 1200 kg/m^3 and polyester density of 60 kg/m^3, thus the fiber blend density is 516 kg/m^2), from coconut (11.1 kt), 27.8 kt fabric or about 54,000 m^3 fiber can be produced (assuming same values as for banana/polyester blend), the cellulose from banana (1670.4 kt) is capable of producing 19,815 kt of paper hand sheet (assuming 84.3% of cellulose in paper pulp (45^0 SR) [64]), from potato (14.3 kt), 16.9 kt can be produced, while coconut (27.7 kt) can produce 32.9 kt. Lignin from banana (358.7 kt) is capable of producing 377.6 kt composite polymer blend material (taking cases of 95% lignin, 5% poly(ethylene) oxide [65]), 13.1 kt from potato (12.4 kt), while coconut (20.4 kt) has a potential to produce 21.5 kt.

3.2.4 Bioenergy potential

Related to biogas production, from Table 4, banana waste streams have potential to give 173.6 (981.7 GWh), 54.0 (305.4 GWh), 16.2 (91.6 GWh), 12.5 (70.7 GWh), 12.2 (69.0 GWh), 1.2 (6.8 GWh) million m^3 biogas (energy equivalent) from pseudostem, peel, leaves, stock, pulp and buds respectively, totaling to 269.7 million m^3 or 1525.2 GWh biogas energy potential (energy conversion is 6.5 KWh per m^3 biogas and considering transportation and biodigester self-consumption of about 13% [57, 62]). Bioethanol energy can potentially be produced from pseudostem 27.6 (189.7 GWh), peels 5.0 (34.4 GWh), leaves 4.2 (28.8 GWh), stock 3.9 (26.8 GWh), pulp 2.8 (19.2 GWh) and bud 0.1 (0.7 GWh), with a potential total of 43.6 kt or 299.6 GWh (Calculated from the lower heating value (LHV) of 1 kg of EtOH generating 7.47 KWh energy and transportation energy consumption of 8% [58, 62]). Potato peel and mix waste have a potential to produce 13.7 (77.4 GWh) and 14.0 (79.2 GWh) million m^3 biogas, and about 5 kt (34.4 GWh) and 1.7 kt (11.6 GWh) potential bioethanol respectively, totaling to about 6.7 million m^3 (156.6 GWh) biogas and 6.7 kt (46.0 GWh) bioethanol. While for coconut wastes, the husk and shell are capable of giving about 9.9 (56 GWh) and 3.4 (19.2 GWh) million m^3 biogas respectively totaling to 13.3 million m^3 (75.2 GWh) biogas, with only the coconut husk being able to give 1.5 kt (10.3 GWh) bioethanol

The biogas energy realizable from banana waste (1525.2 GWh) (which can be converted 40% to electricity and 50% to heat [66]) is capable of producing 610.1 GWh electricity/year and 762.6 GWh heat/year to support (at an average consumption of 620 KWh electricity and 600 KWh heat per year per house hold) about 984,032 and 1.3 million households per year respectively. Bioethanol energy from banana waste has a potential to generate 299.6 GWh/year of heat energy/year capable of supporting about 499,333 households. Biogas from potato (156.6 GWh) has a potential to generate 62.6 GWh electricity and 78.3 GWh heat per year capable of supporting about 100,967 and 130,500 households per year respectively while 46 GWh potential heat energy from bioethanol can support 76,666 households. Potential biogas energy from coconut waste (75.2 GWh) having the potential to generate 30.1 and 37.6 GWh of electricity and heat/year capable of supporting 48,548 and 62,666 households per year while bioethanol energy (1.5 kt or 10.3 GWh) can support 17,166 households. Overall, production biogas as a source of energy has more potential than bioethanol production.

3.3 The overall Potential of waste valorization

Figure 1, given in Sect. 2.1, illustrate the supply chains for banana, potato and coconut produce and the corresponding wastes generated at each stage. From Fig. 1, it is evident that wastes generated at the farm gate, supply line 2 and 3 such as pseudostem, leaves, buds, damaged tubers and coconut husks are centrally generated in the farms. Similarly, wastes given by supply line 6 and 11 such as stock, and rejects and those from factory processing such as peels, rejects and shells are also centrally generated thus, are easier to collect. Conversely, the by-products that are generated at the last two stages of the supply chain (line 12 and line 13) such as wastes from retailers, household and restaurant processing are more widely dispersed. For example, *hawking* or street vending, a common method of retailing in Kenya, typically involves vendors constantly moving from one street to the other with their merchandise in search of buyers [67]. This method of selling covers a wide random area, without a strategy of waste collection, consequently spreads the generated wastes over a winder area. Nevertheless, for centralized customers and restaurants, with the introduction of waste segregation and collection arrangements, a significant quantity (at least 50 %) of peels and rejects can be recovered. Thus, in general, all waste streams from bananas, potatoes and coconut have the potential for valorization except those generated at retailing, household and restaurant processing stage, which might better be mixed with other organic wastes towards composting or digestion (Table 5**)**.

Considering the waste biomass availability, occurrences and current destination as summarized in Table 5, it is evident that all waste streams have high to medium potential for biorefining of various indicated biomaterials. However, an effort to recover the biomaterial should take into account the moisture content. For example, nut wastes have low moisture content, thus, are durable and can be stored for a longer period before use, while all other wastes have high moisture content hence are susceptible to decay, therefore, they might need drying before a delayed use or should be used within few days after harvesting, which might pose storing challenge.

E-supplementary data of this work can be found in online version of the paper.

Conclusion

Bio-waste generation and analysis in Kenya was mapped for banana, potatoes and coconut Large quantities of waste are generated over the value chain (such as banana (6007 kt), potato (426 kt) and coconut (49.5 kt)) with the bulk being generated centrally and thus relatively feasible for collection and biorefinery. All waste streams can be valorized via different valorization routes to produce different bioresource. From the three selected biomass types, we can valorize flavonoids (88.3 kt), starch (377 kt), cellulose (2000.7 kt) and biogas (1757.0 GWh), offering a huge potential for the Kenyan bioeconomy. Further, the results of the study can inform policy making on waste management systems.

Declarations

Declaration of Competing Interest

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.

Acknowledgements

The authors hereby acknowledge that this research work has been conducted within the framework of the TEAM project ‘Towards a more integrated management of organic waste in Kenya; the production of natural dyes from fruit and vegetable waste’, Project no. KE2018TEA464A103 with financial support from the VLIR-UOS, Belgium.

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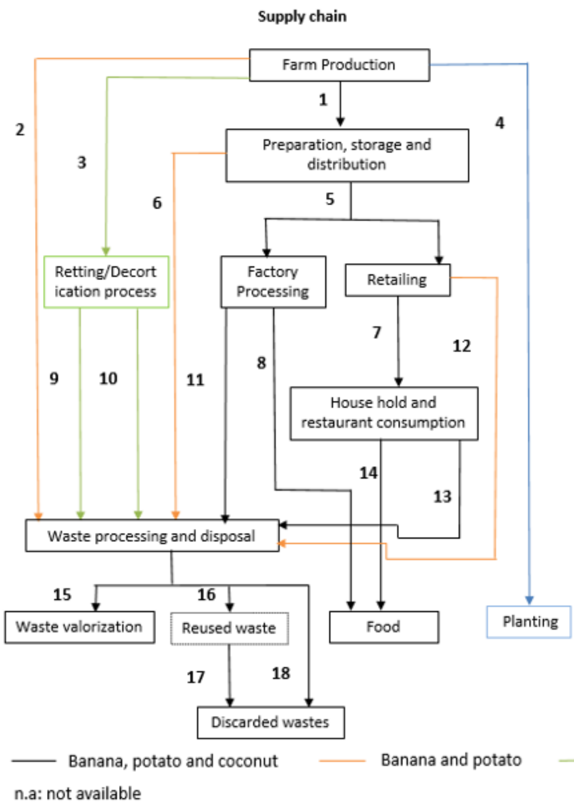
Figures



Product and waste parts

	Banana	Potato	Coconut
1	fruit	tuber	dehusked nut, madafu
2	leaves, pseudo-stem, bud	damaged tuber	n.a
3	n.a	n.a	husk
4	n.a	seed	negligible
5	fruit	tuber	dehusked nut
6	stock	reject	n.a
7	fruit	tuber	dehusked nut
8	pulp	pulp	oil, water, meat
9	n.a	n.a	fiber
10	n.a	n.a	dust
11	peel	peel	shell
12	n.a	reject	n.a
13	peel	peel, reject	shell
14	food pulp	food tuber	copra, oil, water, cake
15	feed, compost, mulch, others	feed, compost, mulch	Soil improver, charcoal
16	rope, wrapping, construction, play item	n.a	broom, mat/matress artifact
17, 18	land/water fill, left to rot, burned	land/water fill, left to rot, burned	land/water fill, left to rot, burned

Figure 1

Kenyan agricultural production supply chain

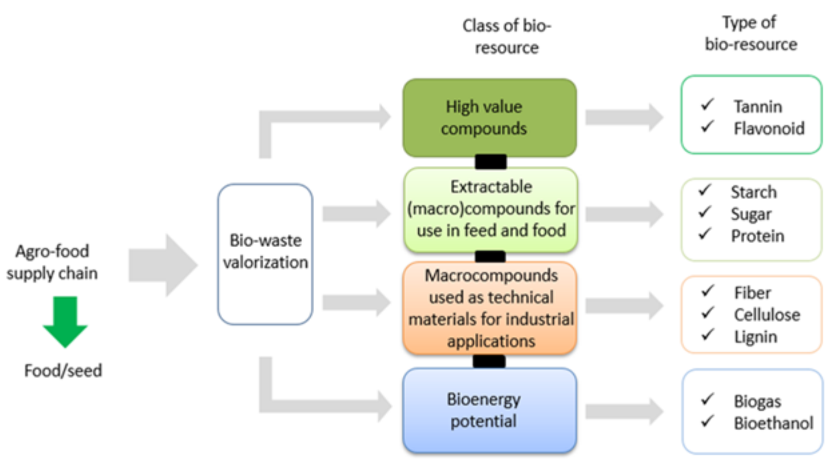


Figure 2

Classification of recoverable biomaterial resource

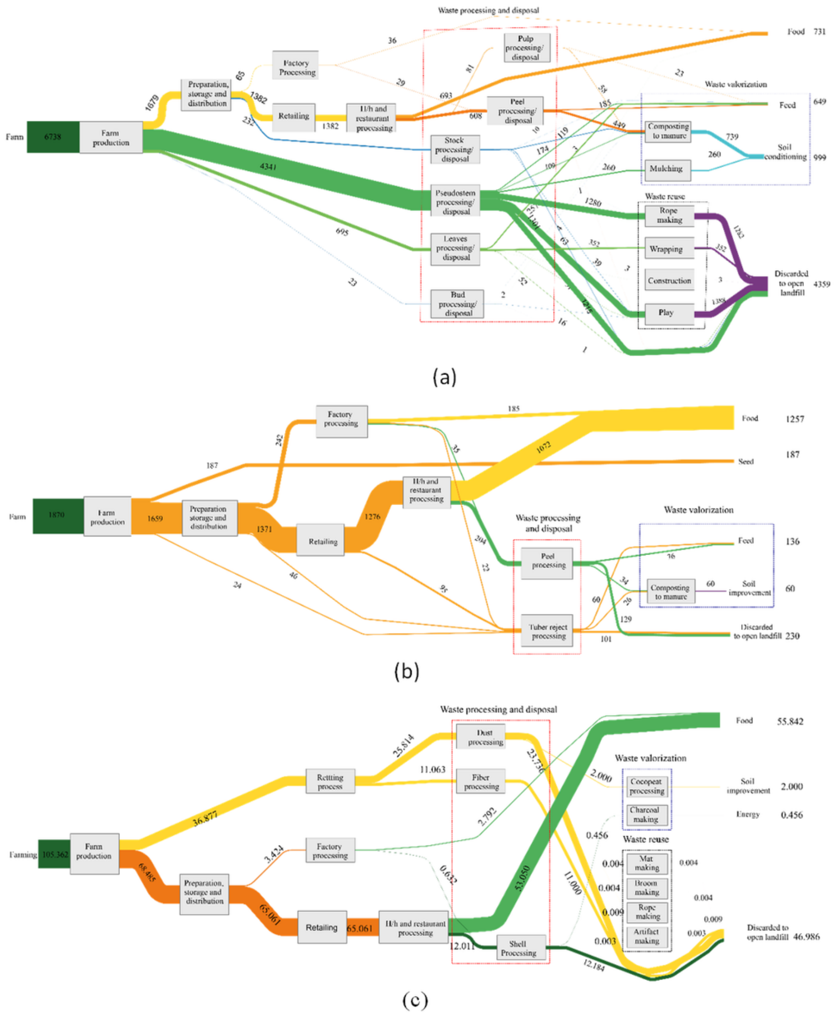


Figure 3

MFAdiagram of by-products in fresh weight basis (a) banana (kt), (b) potato (kt) and (c) coconut (t)

Supplementary Files

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