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Quantifying and monetising externalities in Kenya's green bean value chain: implications for stakeholder and policy actions

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ABSTRACT

Growing international demand for fresh green beans is driving producers in Kenya to expand and intensify crop production for export, creating negative environmental, health and social externalities (hidden costs). However, empirical evidence on the magnitude of these externalities remains limited. Estimating these externalities to reveal their magnitude could encourage stakeholder and policy actions that ensure a more environmentally sustainable, health-protective and socially equitable value chain. This study quantified and monetised negative environmental, health and social externalities in Kenya's green bean value chain. True cost accounting approaches, including life cycle assessment, disability-adjusted life years, the True Price methodology and the value of statistical life years, were used to analyse data from secondary sources. The total hidden costs were estimated at 124.03 million USD (range 115.93–132.20), at least twice the 53.92 million USD market value of green beans and almost three times the export value (42.15 million USD). Environmental externalities accounted for 86.87 million USD (range 79.16–94.65), driven mainly by scarce blue water use and greenhouse gas emissions. Health externalities accounted for 0.97 million USD (range 0.58–1.36), primarily from pesticide exposure. Social externalities (36.20 million USD) reflected a large living income gap among smallholder farming households and the presence of child labour. In conclusion, Kenya's green bean value chain creates substantial negative environmental, health and social externalities. There is a need for stakeholder and policy actions to internalise externalities in the value chain. The findings can guide stakeholders and policymakers in developing and implementing strategies to reduce externalities.

1. Introduction

Growing international demand for fresh produce drives producers to expand and intensify crop production for export, creating substantial hidden costs (negative externalities) [1]. Negative externalities affect the environment (such as air, soil and water pollution and climate change), human health and social welfare (such as child labour and low wages), but are not fully accounted for in current market prices [2]. Kenya's green bean value chain is a pertinent example of a fresh produce value chain that has responded to international market growth while creating negative externalities [3]. Green beans in Kenya are primarily grown for export, with the value chain relying on fertilisers, pesticides, manual labour, irrigation and refrigeration that generate negative environmental, health and social externalities [3–5].

Estimating the negative externalities in the green bean value chain to reveal their magnitude could encourage stakeholder and policy actions that ensure a more environmentally sustainable, human health-protective and socially equitable value chain. Specifically, reducing negative externalities requires a systematic and transparent identification, quantification and monetisation of externalities through true cost accounting approaches and recommending targeted stakeholder and policy actions to internalise them [6]. Internalising externalities means compensating for, preventing, reducing, restoring or stopping negative environmental, health and social impacts through voluntary actions, incentives, disincentives or sanctions across value chains [7].

Negative externalities in global food value chains are not directly obvious in farm or business balance sheets, or national gross domestic product [6]. However, annual global estimates in 2021 indicated that negative externalities in food system were twice as high as the amount spent on purchasing food, that is, about 19.8 trillion United States dollars (USD) compared to nine trillion USD on food purchased at market prices [8]. These costs comprised seven trillion USD (range 4–11) in

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environmental costs, 11 trillion USD (range 3–39) in health costs and one trillion USD (range 0.2–1.8) in social costs, estimated at the middle bound of estimates [8]. Following the publication of this estimate, interest in food systems externalities has increased, with the Food and Agriculture Organisation of the United Nations (FAO) [9] conducting a parallel analysis and estimating the annual global estimate of food system environmental, health and social externalities in 2023 at 12.7 trillion USD at 2020 purchasing power parity (PPP) for the lower bound. The FAO's State of Food and Agriculture (2023) estimate claimed that global negative externalities had a 95 % chance of being 10.87 trillion USD at 2020 PPP or higher and a five per cent chance of being 16 trillion USD at 2020 PPP or more [9].

There is a need for more analyses to estimate negative externalities for regions and specific value chains to inform future food system transformation directions and identify suitable policies to mitigate negative externalities and their consequences [9]. Yet, few studies of food system externalities have been conducted at the global level [8–10], and very few studies have quantified externalities in Africa's food systems [10,11]. More targeted, context-specific studies of Africa's externalities in the food systems are needed to facilitate the development of better-suited policies and interventions to reduce negative externalities and build more sustainable food systems and value chains [12].

Green beans are Kenya's largest vegetable export, accounting for at least 25 % of the volume and 19 % of the value of total fresh vegetable exports while generating income for many farmers, packhouse operators, workers and traders [3,13]. There has been substantial growth in Kenya's green bean exports to countries such as Belgium, France, the Netherlands and the United Kingdom, increasing from 16,841 tonnes in 2018 to 19,417 tonnes in 2022 [14]. In 2022, Kenya was Africa's second-largest exporter of green beans, after Morocco, supplying the produce year-round [14,15]. The global export market for green beans was 755,767 tonnes in 2021 [14] and demand is steadily growing at 3.5 % annually [16]. Meeting the future needs of a growing market will require expanding and intensifying green bean farming in Kenya and other countries, increasing negative environmental, health and social externalities. These externalities can hinder the achievement of Sustainable Development Goals (SDGs), including SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 4 (education), SDG 6 (clean water and sanitation), SDG 10 (reduced inequality), SDG 12 (responsible consumption and production), SDG 13 (climate action) and SDG 15 (biodiversity on land) [17,18].

However, empirical evidence on the current magnitude of negative externalities in Kenya's green bean value chain remains limited. Although a few studies have quantified negative environmental and health externalities in Kenya's green bean value chain [3,19,20], many relevant externalities, including social impacts, remain unestimated. Moreover, no study has monetised negative externalities in the green bean value chain in Kenya or elsewhere. Monetising externalities into a single currency (US dollars) allows comparison of hidden costs across value chain stages, with prices and between value chains. This study was conducted to quantify and monetise negative environmental, health and social externalities in Kenya's green bean value chain, providing empirical insights to guide stakeholders and policymakers in developing and implementing strategies to reduce externalities.

This study demonstrated methodological novelty by integrating life cycle assessment, disability-adjusted life years, the True Price methodology (monetisation factors) and the value of statistical life years to simultaneously estimate negative environmental, health and social externalities. Estimating these externalities filled a research gap in nexus-type studies called for by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in its ongoing assessment of the nexus of biodiversity, climate change, food, health and water [21]. Exposing the true costs of Kenya's green bean value chain can inform benchmarks and targets for internalising negative externalities in this value chain and similar value chains to ensure sustainable value chains.

2. Literature review

2.1. Environmental, health and social externalities in Kenya's green bean value chain

About 52,000 smallholder farm households produce 60 % of all green beans harvested annually in Kenya [3]. Large-scale farmers, comprising individual farmers and exporters (or exporting companies), account for approximately 40 % of all green beans produced annually in Kenya [3]. Approximately 37 % of the green beans harvested annually in Kenya are rejected at the production stage of the value chain as they do not meet the quality standards for export [22]. The rejected beans are sold in Kenyan markets for consumption by households and in restaurants (33.33 %), used as animal feed by cattle keepers (33.33 %) and turned into compost (33.33 %) [19]. In 2022, Kenya produced approximately 69,124 tonnes of green beans on 8,228 ha (ha), implying that one tonne of the crop occupied 0.12 ha [13]. In addition, farmers sold green beans at an average farmgate price of 420 USD (1 USD = 117.74 Kenya shillings (KES)) per tonne [13,23], compared to the average export price of 2171 USD [14]. Traders sold some green beans domestically at an average market price of 780 USD per tonne [24].

Kenya's green bean value chain generates negative externalities. Chemical pesticides, inorganic fertilisers, refrigerated trucks and energy used to operate cold rooms cause air pollution, which can lower environmental quality [3,25]. Stoves used by domestic consumers to cook green beans also cause air pollution [20]. These air pollutants are associated with acidification, particulate matter formation, photochemical oxidant formation and ozone layer depletion [26]. Soil pollution resulting from fertiliser and pesticide use can contribute to terrestrial, freshwater and marine ecotoxicity, posing risks to soil and water ecosystems, including beneficial bacteria, insects and fish [25,26]. Run-off from green bean fields treated with inorganic fertilisers contributes to water pollution, including freshwater eutrophication (phosphorus emissions) and marine eutrophication (nitrogen emissions) [26,27]. Eutrophication can harm aquatic life and lower drinking water quality [20].

The land occupation involves using grassland or savannah to produce green beans, making it unavailable for biodiversity and ecosystem services [19,20]. Land transformation entails using grassland or savannah to cultivate green beans, leading to a reduced size of habitats and ecosystems and the loss of biodiversity [19,20]. Continuous land cultivation and monocropping of green beans contribute to soil degradation through soil organic carbon loss [3]. Green bean production requires sufficient water for irrigation, mostly pumped from rivers [3,27]. Most farmers use diesel-powered generators to pump water for furrow irrigation, contributing to climate change through greenhouse gas (GHG) emissions and blue water scarcity [3,19,27]. Blue water scarcity is exacerbated by using surface water from rivers and lakes and groundwater from aquifers to wash fresh green beans and packhouses and cook the beans [20,25]. Other causes of GHG emissions include inorganic fertilisers, pesticides, refrigerated trucks, cold rooms and composting green beans [3,20].

Air pollutants such as ammonia and photochemical oxidants from fertilisers, pesticides, diesel (used in cultivation tractors, irrigation pumps and trucks) and energy used to operate cold rooms can cause human toxicity [3,19,28]. Using electricity, gas, wood and charcoal to cook green beans can emit carbon dioxide and particulate matter, which have health effects [20,29]. Human toxicity from air pollution causes health problems such as respiratory complications and cardiovascular diseases [3,28]. Farmworkers who apply pesticides on green bean farms without protective gear have reported skin irritation, respiratory problems or cancer [3,28,30]. Farm run-off can contaminate local water supplies with pesticides, leading to waterborne diseases [30]. Pesticide residues in green beans can cause foodborne illnesses in consumers [31].

Disposing of wastewater from washing green beans into untreated sewerage can contribute to local water contamination and waterborne diseases [20].

According to the Netherlands Development Organisation [32], underage workers, some of whom are not attending school, are involved in the green bean value chain. The net income received by farm households from the sale of green beans and net wages received by workers across the value chain can not meet households' cost of basic but decent living standards [5,33]. Besides overworking under forced labour and underpaid overtime, many workers lack personal protective equipment, leading to occupational accidents [30]. Employment in the green bean value chain is often casual-based, with reported elements of inequalities (recruitment and wages) and sexual and non-sexual harassment [32].

2.2. Empirical evidence and gaps in estimating negative externalities in food value chains

This section reviews literature that has estimated negative environmental, health and social externalities in food value chains, beginning with studies for other countries and then for Kenya. Ngowi et al. [34] used a cost-of-illness model to estimate the health costs associated with pesticide use on vegetable farms (cabbage, onion and tomato) in Tanzania. The cost-of-illness model captured the direct costs (such as healthcare and medical costs) and indirect costs (such as costs of informal care and lost working days) associated with treating a particular disease related to pesticide exposure [34]. Smallholder farmers' annual health expenditures due to pesticide use ranged from 0.018 USD to 116 USD [34]. This implied that a farmer's health expenditures due to pesticide use accounted for at least 0.1 % of Tanzania's total per capita health expenditure (26 USD) in 2007 [35].

Ilari et al. [25] used life cycle assessment (LCA) to evaluate negative environmental externalities in Italy's green bean value chain. LCA is a widely used methodology for systematically evaluating a product's ecological impacts throughout its life cycle, from production to consumption [36]. The LCA estimates for one tonne of frozen green beans revealed negative impacts comprising 700 kg CO_2-eq for GHG emissions, 0.19 kg C_2H_4-eq (ethene) for photochemical oxidation, 3.5 kg SO_2-eq (sulphur dioxide) for acidification and 1.7 kg PO_4^{3-}-eq (orthophosphate) for eutrophication [25]. These externalities were attributed to chemical pesticides, inorganic fertilisers, refrigerated trucks and energy used to operate cold rooms. However, Ilari et al. [25] did not monetise the quantified negative environmental externalities due to the limited scope of the analysis.

Likewise, Esmaeilzadeh et al. [37] conducted a life cycle assessment of environmental externalities in onion production in Taiwan. Producing one tonne of onions required approximately 136 m^3 of blue water for irrigation and emitted at least 0.00002 kg CFC11-eq (trichlorofluoromethane) as ozone layer-depleting emissions. The trichlorofluoromethane emissions were attributed to chemical fertilisers and pesticides, farm machinery and electric water pumps. Esmaeilzadeh et al. [37] recommended managing irrigation time and frequency to reduce water use and controlling fertiliser and pesticide use in onion fields. Nevertheless, Esmaeilzadeh et al. [37] did not monetise the quantified negative environmental externalities.

Lloyd et al. [38] applied the non-steady-state static chamber method to measure GHG emissions from cranberry and tomato farms in Canada. The non-steady-state static chamber method is a widely used experimental technique for quantifying GHG emissions from agricultural soils [39]. One hectare of cranberry and tomato production systems emitted approximately 2,700 kg CO_2-eq and 11,000 kg CO_2-eq, respectively [38]. The quantified soil GHG emissions were attributed to the inorganic fertilisers used on farms. However, Lloyd et al. [38] did not monetise the quantified GHG emissions.

Moreover, Wainaina et al. [40] applied the cost of treating wastewater and the cost-of-illness model to estimate the costs of water pollution and waterborne diseases caused by wastewater from coffee processing industries in Ethiopia. The annual costs of treating wastewater were estimated at 5,354 USD, while the costs of treating diseases caused by wastewater use amounted to 54.19 USD per person per dosage in 2017 [40]. Health problems included eye, ear and skin irritation, nausea and stomach pain among local residents. Although Wainaina et al. [40] noted that several negative social externalities were prevalent in Ethiopia's coffee value chain, they did not estimate them.

Some studies have estimated negative externalities in Kenya's food value chains. Macharia [28] applied the cost-of-illness model and the deposit-refund system (DRS) to quantify and monetise negative externalities from pesticide use in the vegetable sub-sector (cabbage, kale and potato) in Kenya between 2003 and 2008. There were substantial annual average costs related to human health (0.65 million USD), livestock loss (2.46 million USD) and pollution control through DRS for empty pesticide containers (0.06 million USD). The negative externalities amounted to 3.17 million USD per year, compared to the direct cost of pesticides of 5.06 million USD in the vegetable sub-sector. On average, one US dollar spent by farmers on pesticides generated external costs of 0.6 USD. Macharia [28] concluded that pesticide use in Kenya's vegetable farms had created substantial negative health and environmental externalities, requiring targeted internalisation measures.

Bergman et al. [41] used the True Price methodology to monetise negative externalities in Kenya's export-oriented tea value chain. Their analysis was limited to social (child labour, gender discrimination, lack of social security and insufficient income) and environmental (air, soil and water pollution, land use and non-renewable energy depletion) externalities. The total external costs of one tonne of green leaf tea in Kenya amounted to 1,200 USD (based on the 2015 exchange rate of 1 USD = 0.912 EUR), comprising 770 USD from cultivation, 50 USD from transportation, 330 USD from processing and 50 USD from packaging [41]. These costs (1,200 USD) were at least three times the retail price (380 USD) of one tonne of green leaf tea in Kenya. Yet, the authors explained that some relevant negative externalities, including health externalities, were not included in the analysis due to data unavailability.

Likewise, the Impact Institute [42] used the social impact scan method to estimate social costs in Kenya's export-oriented rose value chain in 2020. On top of the retail price of 1.35 USD, the social costs of producing one rose stem totalled 0.039 USD (1 USD = 0.822 EUR). The drivers of these costs were gender discrimination (0.021 USD), underpayment (0.010 USD), lack of social security (0.007 USD) and employee health and safety (0.001 USD) [42]. Moreover, the Impact Institute [43] applied the True Price methodology to estimate environmental externalities in Kenya's coffee value chain in 2022. The total environmental costs of one tonne of coffee summed to 1578.14 USD (1 USD = 0.9239 EUR), comprising air pollution (205.66 USD), contribution to climate change (64.94 USD), fossil fuel depletion (21.65 USD), land use (508.73 USD), scarce water use (10.82 USD), soil pollution (10.82 USD) and water pollution (768.48 USD). However, the Impact Institute [42] and Impact Institute [43] did not estimate negative health externalities in Kenya's rose and coffee value chains, respectively.

Kleih et al. [3] applied LCA and disability-adjusted life years (DALYs) to quantify negative environmental and health externalities in Kenya's green bean value chain. DALYs were used as a quantitative measure of the overall disease burden, expressed as the number of years lost due to disability, early death, or ill health [44]. One tonne of fresh green beans at the farm gate had a global warming potential of 89.3–565 kg CO_2-eq and 8170 to 8,890 kg CO_2-eq at the market gate. Health externalities at free-on-board ranged from 0.0017 to 0.0031 DALYs and 0.015 to 0.016 DALYs at market-gate, while ecosystem damages at free-on-board ranged from 0.000034 to 0.00006 species/year and 0.000098 to 0.000124 species/year at market-gate. The main drivers of the quantified externalities included chemical fertilisers and pesticides used in green bean production, diesel-powered water pumps, trucks and refrigeration. Similarly, Basset-Mens et al. [19] used LCA to analyse the green bean value chain and found that transporting one tonne of fresh green beans from Kenya to the United Kingdom emitted about 8,000 kg CO_2-eq. However, Kleih et al. [3] and Basset-Mens et al. [19] did not monetise the quantified negative externalities. Additionally, the authors explained that many relevant environmental, health and social externalities were not quantified due to data unavailability.

Supplementary Table 1 summarises the empirical studies of negative externalities in food value chains. Overall, analyses in most studies have not included many relevant negative environmental, health and social externalities in food value chains due to data unavailability, time constraints, or scope limitations. In addition, many studies have not monetised negative environmental, health and social externalities in food value chains. Moreover, only a few studies have simultaneously assessed any combination of negative environmental, health and social externalities in food value chains. Revealing all the various negative environmental, health and social externalities of food value chains is challenging, as there is no single method for estimating all these externalities [45,46]. Therefore, estimating each specific externality requires a distinct method [45,47].

Although a few studies have quantified negative environmental and health externalities in the green bean value chain in Kenya and other countries [3,19,25], the authors explained that they excluded many relevant externalities, including social impacts, due to data unavailability or scope limitations. Still, no study has monetised negative externalities in the green bean value chain. There is a need for a study to simultaneously quantify and monetise negative environmental, health and social externalities in Kenya's green bean value chain to inform stakeholder and policy actions for reducing externalities.

3. Methods and procedures

3.1. Scope, system boundaries and data sources

The functional unit of analysis was one tonne of fresh green beans considered at four stages of the value chain, comprising the production (farm), packhouses, trade (port) and consumption within Kenya, as shown in Fig. 1. Many studies on negative externalities in agricultural value chains focus on footprints per kilogram or tonne of product, regardless of potential yield differences per hectare among farmers [3,25,48]. Estimating negative externalities per tonne rather than per hectare of fresh green beans allows comparison of hidden costs (negative externalities) across value chain stages, with prices and between value chains. The GHG emissions due to air-freighting of fresh green beans from Kenya's Jomo Kenyatta International Airport to Heathrow Airport in the United Kingdom were also quantified. The United Kingdom was selected as a reference destination due to data availability and because it received the highest volume of Kenya's green bean exports in 2022 (6,606 tonnes), compared with France (6,068 tonnes), the Netherlands (4,442 tonnes) and Belgium (1,091 tonnes) [14].

Although several negative environmental, health and social externalities were identified in Section 2.1, only the externalities for which data were available were estimated. For example, the identified social externalities such as forced labour, gender discrimination, harassment, underpayment and lack of health, safety and social security were not analysed due to data unavailability. The clearly defined scope and system boundaries of the analysis ensured non-redundancy (no double-counting problems) in estimating the negative externalities.

In this study, several credible secondary data sources (peer-reviewed

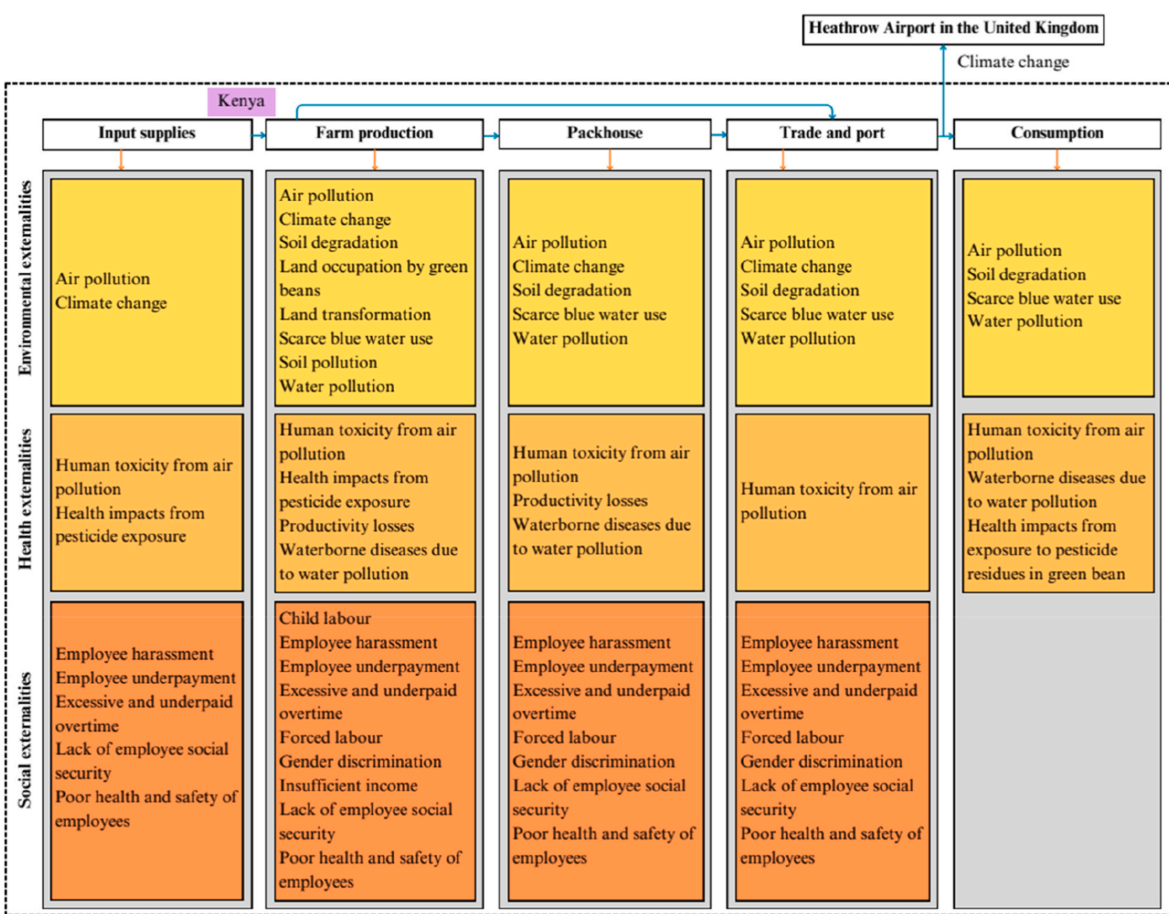

Fig. 1. System boundary for Kenya's fresh green bean value chain. Source: Authors' work. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

journal articles and reputable reports) were used to quantify the negative externalities in Kenya's green bean value chain (see Table 1). Production data was based on green bean yield in 2022, as provided by the Agriculture and Food Authority-Horticultural Crops Directorate (AFA-HCD) [13].

3.2. Quantification of the environmental externalities

The environmental externalities were quantified using a life cycle assessment (LCA), which included emission factors [19], characterisation factors from ReCiPe 2016 [36] and the True Price quantification model [60]. LCA is a widely used methodology for systematically quantifying the environmental impacts of products throughout their life cycle [36,61]. Several studies have applied LCA to evaluate environmental externalities in food value chains [3,25,40]. For these reasons, LCA was a suitable methodology for quantifying environmental externalities across Kenya's green bean value chain from farm production to consumption. LCA data were drawn from several credible secondary data sources (Table 1).

The environmental externalities were captured at the midpoint and endpoint impact levels [36]. Midpoint impacts represent the direct environmental impacts of the value chain [62]. Endpoint impacts refer to the ultimate consequences of these direct environmental impacts on ecosystem quality [36]. Footprint indicators measure the environmental externalities in the value chain in standard reference units [60]. For example, ammonia emission, a footprint indicator for air pollution externality, can be expressed in the reference unit as kg NH_3-eq.

In LCA, emission factors (standard or case-specific values) are used to estimate emissions to the environment [3,19,63]. Emission factors were used to calculate emissions from mineral fertilisers and cattle manure applied to the green beans crop, as shown in equation (1).

$$E = A \times EF \qquad \text{Equation 1}$$

where E was the emission quantity, A was the production activity, such

Table 1
List of negative externalities included in the analysis and data sources.

Externalities	Footprint indicators	Unit	Data sources
Environmental externalities			
Contribution to climate change	Greenhouse gas (GHG) emissions	kg CO_2-eq	Basset-Mens et al. [19], Frankowska et al. [26], Ilari et al. [25], Kleih et al. [3], Poore and Nemecek [49] and Romero-Gámez et al. [50]
Air pollution	Terrestrial ecotoxicity from 1,4 dichlorobenzene (1,4-DB) emissions	kg 1,4-DB-eq emitted to soil	Frankowska et al. [26] and Ilari et al. [25]
	Marine ecotoxicity from 1,4-DB emissions	kg 1.4-DB-eq emitted to seawater	Frankowska et al. [26] and Svanes et al. [51]
	Particulate matter (PM) formation	kg $PM_{2.5}$-eq	Desiderio et al. [52] and Frankowska et al. [26]
	Photochemical oxidant formation from non-methane volatile organic compound (NMVOC) emissions	kg NMVOC	Abad-González et al. [48] and Crenna et al. [53]
	Photochemical oxidant formation from nitrogen oxides (NO_x) emissions	kg NO_x-eq	Abad-González et al. [48] and Crenna et al. [53]
	Acidification from sulphur dioxide (SO_2) emissions	kg SO_2-eq	Frankowska et al. [26], Ilari et al. [25], Milà i Canals et al. [20] and Romero-Gámez et al. [50]
	Ozone layer depletion from trichlorofluoromethane (CFC11) emissions	kg CFC11-eq	Ilari et al. [25], Abad-González et al. [48] and Crenna et al. [53]
	Ammonia emissions (NH_3)	kg NH_3-eq	Basset-Mens et al. [19], Ilari et al. [25] and Kleih et al. [3]
Water pollution	Freshwater eutrophication from phosphorus (P) emissions	kg P-eq to freshwater	Abad-González et al. [48], Frankowska et al. [26], Milà i Canals et al. [20] and Romero-Gámez et al. [50]
	Marine eutrophication from nitrogen (N) emissions	kg N-eq to marine water	Desiderio et al. [52], Frankowska et al. [26] and Kägi et al. [27]
Soil pollution	Freshwater ecotoxicity through toxic emissions to soil	kg 1.4-DB-eq emitted to freshwater	Abad-González et al. [48] and Frankowska et al. [26]
Land occupation by green beans	Land (grassland/savannah) occupation by green beans	mean species abundance (MSA) *ha*yr	Agriculture and Food Authority-Horticultural Crops Directorate (AFA-HCD) [13]
Land transformation	Land ((grassland/savannah) transformation	MSA *ha	Basset-Mens et al. [19] and Frankowska et al. [26]
Scarce blue water use	Scarce blue water use	m^3 scarce water	Basset-Mens et al. [19], Ilari et al. [25], Kägi et al. [27] and Milà i Canals et al. [20]
Soil degradation	Soil organic carbon (SOC) loss	kg SOC	Milà i Canals et al. [20]
Health externalities			
Human toxicity from air pollution	Disability-adjusted life years (DALYs) due to toxic emissions to air	DALY	Herrera-Araujo et al. [54]
			Basset-Mens et al. [19]
Health impacts from pesticide exposure	Disability-adjusted life years (DALYs) due to exposure to pesticides	DALY	Kleih et al. [3]
Social externalities			
Child labour	Underage workers below minimum age for light work (5–12 years) involved in non-hazardous economic work Underage workers above the minimum age for light work and below the minimum age (13–15 years) involved in non-hazardous and non-light economic work Workers above minimum age (16–17 years) and below 18 involved in hazardous work Underage workers that are not attending school	Child full-time equivalent (FTE) and number of children not attending school	FAOSTAT [55] International Labour Organisation [56] Kenya National Bureau of Statistics [57] United Nations Children's Fund [58] United Nations Children's Fund [59]
Insufficient income for farmers	Living income gap	United States dollars (USD)	Alliot et al. [5] and the United States Agency for International Development (USAID) [33]

Source: Authors' compilation based on references indicated in the table.

as kilogram of specific fertiliser or nutrient from manure applied and *EF* represented the emission factor for the activity [64].

As applied by Kleih et al. [3] and Basset-Mens et al. [19] in quantifying farm production emissions, an emission factor of two per cent (2 %) was used to calculate ammonia emissions from calcium ammonium nitrate and di-ammonium phosphate. According to the Beef Cattle Research Council [65] and Andrew Palmer [66], one tonne of cattle manure contains about 6 kg of nitrogen. Ammonia emissions from cattle manure used on the green bean at a rate of 15 tonnes per hectare were modelled based on an emission factor of 20 % of the nitrogen content of cattle manure as applied by Kleih et al. [3] and Basset-Mens et al. [19].

In LCA, life cycle impact assessment (LCIA) models are used to estimate environmental impacts by means of characterisation factors [36, 67]. Characterisation factors are numerical values used to convert different environmental impacts into a standard reference unit, such as per kilogram (kg) of emissions released or input used, in LCAs [36]. Any footprint indicator data that was not captured in the standard reference unit was multiplied by globally applicable characterisation factors (Supplementary Table 2) from the Dutch National Institute for Public Health and the Environment's ReCiPe 2016 (Hierarchist) LCIA database [36] and Arendt et al. [68]. For example, freshwater eutrophication, a footprint indicator for water pollution externality, was expressed in kg P-eq [7]. If one kilogram of phosphate ion (PO_4^{3-}-eq) was equivalent to a characterisation factor of 0.33 kg P-eq, a 10 kg PO_4^{3-}-eq was converted to 3.3 kg P-eq following the True Price quantification model (Equation (2)).

$$FI_i = x_i CF_i \qquad \text{Equation 2}$$

where FI_i was the value for a footprint indicator in a standard unit, such as kg P-eq, x_i was the value for the indicator in a different unit, such as kg PO_4^{3-}-eq and CF_i was the characterisation factor, representing how much an emission type x_i contributed to freshwater eutrophication in kg P-eq per tonne fresh green beans [69].

After calculating the environmental footprints using emission and characterisation factors, a mean estimate was calculated (for each footprint indicator) at each green bean value chain stage, as expressed in equation (3).

$$FI_{\hat{\mu}} = \frac{\sum_{i=1}^{n} FI_i}{n} \qquad \text{Equation 3}$$

where $FI_{\hat{\mu}}$ was the mean estimate for a footprint indicator at a specific stage of the green bean value, FI_i was the indicator's footprint in a standard unit and n represented the number of data points for all $i = 1, 2, \ldots, n$ [70].

The mean estimates for the footprint indicator at different stages of the value chain were then summed up to obtain the total footprint across the green bean value chain, as shown in equation (4).

$$FI_t = \sum_{i=1}^{n} FI_{\hat{\mu}} \qquad \text{Equation 4}$$

where FI_t was the estimated total mean footprint for the indicator across the green bean value chain and $FI_{\hat{\mu}}$ were the mean footprints at each value chain stage for all $i = 1, 2, \ldots, n$ [70].

3.3. Quantification of health externalities

The disability-adjusted life years (DALYs) were used to quantify health externalities in the green bean value chain in Kenya. DALYs are a quantitative representation of a population's overall disease burden, expressed as the number of years lost due to disability, early death, or ill health [44]. DALYs allow the aggregation of various health impacts, such as human toxicity from air pollutants and health impacts from pesticide exposure, into a single comparable metric [3,71], making it suitable for quantifying negative health externalities in the green bean value chain. Moreover, several studies have used DALYs as a quantitative measure for health externalities in food value chains [3,71,72].

Human toxicity from air pollutants (ammonia, particulate matter, photochemical oxidants and ozone layer-depleting emissions) and health impacts from pesticide exposure were adopted from Basset-Mens et al. [19] and Kleih et al. [3] based on Equation (5).

$$DALY = YLL + YLD \qquad \text{Equation 5}$$

where *YLL* was the years of life lost due to premature mortality and *YLD* was the years of life lived with disability due to a particular health condition [71]. The average DALYs per tonne of fresh green beans for human toxicity from air pollutants and health impacts from pesticide exposure were calculated.

3.4. Quantification of social externalities

Child labour was measured as child full-time equivalent (FTE), implying a full-time job of 40 hours per week [73,74] and the number of underage workers not attending school. The number of child labourers not attending school was captured to measure the impact of child labour on children's education and future opportunities, as recommended by Galgani et al. [7], the International Labour Organisation [56] and the Kenya National Bureau of Statistics [57].

Approximately 1,468,816 out of 17,280,193 (8.5 %) children aged 5–17 years were considered to be underage workers across all sectors in Kenya based on statistics provided by the United Nations Children's Fund [58] and the United Nations Children's Fund [59]. Estimating the number of child labourers was challenging, as the available data was not specific to value chains or sectors, but rather to the entire Kenyan economy.

Three steps were followed to quantify child labour in Kenya's green bean value chain. In step one, the average percentages of underage workers of 5–12 years (78.4 %), 13–15 years (19.4 %) and 16–17 years (2.2 %) [57] were each multiplied by 1,468,816 to calculate the number of underage workers per age set in the entire economy. This outcome was then multiplied by the average percentage (52 %) of underage workers in the agricultural sector adopted from the Kenya National Bureau of Statistics [57] to obtain the number of child labourers per age set.

In step two, the number of child labourers per age set in the agricultural sector was divided by Kenya's land area (27,710,000 ha) used for agriculture, as reported by FAOSTAT [55], to obtain the numbers of underage workers (5–12, 13–15 and 16–17 years) per hectare. These were then multiplied by 0.12 ha (land area occupied by one tonne of green beans in 2022) to obtain the number of children per age set in child labour per tonne of green beans.

In step three, the minimum working hours per age set per week reported by the Kenya National Bureau of Statistics [57] as one hour (5–12 years), 14 hours (13–15 years) and 42 hours (16–17 years) and an FTE of 40 hours per week [74] were used to calculate child FTE per tonne of green beans, as shown in Equation (6).

$$\text{Child FTE} = \frac{CCL \text{ x } HW}{FTE} \qquad \text{Equation 6}$$

where *CCL* was the number of children per age set in child labour per tonne of green beans, *HW* represented the minimum working hours per age set per week and FTE = 40 h per week.

Finally, child labour was calculated as the number of underage workers not attending school. According to the International Labour Organisation [56], 12.7 % of underage workers in Kenya are not attending school. Therefore, 12.7 % of the total number of underage workers per tonne of green beans was computed to obtain the number of underage workers not attending school. Using the national proportion of child labourers not attending school was consistent with standard practice when sector or value chain-level disaggregation is unavailable [75].

Insufficient income was measured by the living income gap footprint indicator in US dollars based on the 2022 annual average exchange rate obtained from the Central Bank of Kenya [23] (1 USD = 117.74 Kenya shillings (KES)). The living income gap concerned smallholder farmers in Kenya's green bean value chain with an income below what was necessary for a decent living standard in 2022 [5]. The living income gap was estimated using the True Price method [76], as expressed in Equation (7).

$$LIG = \frac{LIB - NI}{Q} \quad \text{Equation 7}$$

where *LIG* was the living income gap per tonne of green beans, *LIB* was the household's annual living income benchmark, *NI* was the household's annual net income from green beans and *Q* represented the quantity of green beans produced by the household in 2022.

The living income benchmark (LIB) entailed the annual cost of a basic but decent living standard for a household farming green beans in Kenya, including affordable and nutritious food, contingency expenses, education, health care and housing [5]. In 2017, a household farming green beans had a living income benchmark of approximately 2,259.22 USD (266,000 KES) [5]. This value was adjusted using a 32.7 % annual consumer price index (CPI) inflation rate [77] to obtain 2,997.13 USD (352,882 KES) equivalent in 2022. The annual inflation rate (R) and the adjusted LIB were calculated as shown in equations (8) and (9) [78].

$$R = ((\text{CPI in current year} \div \text{CPI in base year}) - 1) \times 100 \quad \text{Equation 8}$$

$$LIB_{2022} = LIB_{2017} \times \frac{100 + R}{100} \quad \text{Equation 9}$$

A typical household was assumed to farm green beans on one acre of land [3], producing about 3.4 tonnes of green beans and selling these at an average farmgate price of 420 USD (50,000 KES) per tonne [13]. The cost of green bean production per acre in 2015, estimated at 624.26 USD by the United States Agency for International Development (USAID) [33], was adjusted using a 52.3 % annual CPI inflation rate [77] to obtain a 950.78 USD equivalent in 2022. As each household received roughly 1,443.86 USD from selling 3.4 tonnes of green beans, the gross margin (household's net income) was calculated as 493.08 USD in 2022. The net income, the living income benchmark and the quantity of green beans produced by a household were used to calculate the living income gap per tonne of green beans in 2022.

3.5. Monetisation of the environmental and social externalities

The valuation of environmental and social impacts was conducted using the True Price methodology. This methodology was chosen because it incorporates monetisation factors for a range of environmental and social externalities based on the abatement, compensation, prevention, restoration and retribution costs approach [7]. Monetisation factors are estimated monetary weights that can be used to express the environmental and social externalities in monetary units so that they are comparable to each other and to food prices [46]. The True Price monetisation factors [7] were used to estimate the costs of environmental and social externalities in Kenya's green bean value chain, as they are globally applicable. Moreover, other studies have already applied the True Price methodology and monetisation factors to estimate the environmental and social costs of Kenya's coffee [43] and tea [41] value chains.

The globally applicable monetisation factors in Appendix A were adjusted using Kenya's 7.7 % annual CPI inflation rate between 2021 and 2022 [77], as shown in equation (10).

$$MF_{2022} = MF_{2021} \times \frac{100 + R}{100} \quad \text{Equation 10}$$

where *MF* was the monetisation factor and *R* was the annual CPI inflation rate (7.7 %).

For example, MF_{2022} = 0.2412 USD/kg CO_2-eq (0.224 USD in 2021) based on Galgani et al. [7], represented the abatement cost as a marginal value for reducing GHG emissions to meet the two-degree climate targets from a global meta-analysis. It aligned the contribution of GHG emissions to climate change and associated damages with what emissions should cost if fully internalised. Unlike the globally applicable MF provided by Galgani et al. [7], the World Bank's carbon prices (mostly carbon taxes) for countries are not directly comparable due to differences in politics, coverage, compliance and compensation arrangements [79]. For example, South Africa's (the only African country listed on the World Bank's carbon pricing dashboard) or the Netherlands' carbon prices can not be used for Kenya.

A monetisation factor was applied to each footprint indicator at each value chain stage as specified in Equation (11).

$$MFI_{\hat{\mu}} = FI_{\hat{\mu}} \times MF_i \quad \text{Equation 11}$$

where $MFI_{\hat{\mu}}$ was the monetary mean estimate for a footprint indicator (average external cost) at a specific value chain stage, $FI_{\hat{\mu}}$ was the estimated mean quantity for the footprint indicator and MF_i was the monetisation factor [60].

The mean estimates of external costs for the footprint indicator at different value chain stages were then summed up to obtain the total external costs across the value chain (equation (12)).

$$MFI_t = \sum_{i=1}^{n} MFI_{\hat{\mu}} \quad \text{Equation 12}$$

where MFI_t was the total monetary mean estimate for the footprint indicator (total average external costs) across the value chain and $MFI_{\hat{\mu}}$ were the estimated average external costs at each stage of the value chain for all $i = 1, 2, ..., n$ [70].

The above calculations in Equations (11) and (12) were related to a functional unit of one tonne of fresh green beans. Considering the entire quantity of green beans (69,124 tonnes) produced in Kenya in 2022, various tonnes of green beans per value chain stage (Table 2) were factored in when calculating footprint costs.

The estimated external cost for each environmental footprint indicator per tonne of green beans at each stage (Equation (11)) was multiplied by the amount of green beans allocated to that stage (Table 2) to obtain an average external cost for the footprint indicator for all green beans. These average external costs for the footprint indicator at different stages were summed up to get the total average external cost for all green beans across the value chain. For the living income gap (social footprint indicator for insufficient income to farmers), 41,474

Table 2
Quantities of green beans in 2022 per value chain stage included in the analysis.

Value chain stages	Quantity (tonnes)	Explanation
Production	69,124	Total production in 2022
Domestic packhouses	43,548	Total output in 2022 minus 37 % (25,576 tonnes) of green beans rejected for export at the production stage
Domestic trade and port	35,986	Green beans for the domestic market (8,525 tonnes from production and 8044 tonnes from domestic packhouses) plus 19,417 tonnes to the port of export
Domestic consumption	16,569	Green beans for domestic consumption (8,525 tonnes from production plus 8044 tonnes from domestic packhouses)
Food loss and waste	16,569	Green beans used as compost (8,525 tonnes from production plus 8044 tonnes from domestic packhouses)

Source: Authors' work based on AFA-HCD [13], Kleih et al. [3] and International Trade Centre [14].

tonnes (60 % of 69,124 tonnes) of green beans produced by smallholder farmers were considered.

To this end, the monetisation procedures have pointed to the valuation of various footprint indicators' impacts. The estimated external costs for various footprint indicators that measure a common externality were summed up to obtain the costs associated with that externality across the value chain, as specified in Equation (13).

$$\mathrm{ME} = \sum_{i=1}^{n} \mathrm{MFI}_t \qquad \text{Equation 13}$$

3.6. Monetisation of health externalities

Human health externalities were monetised following the value of statistical life years (VSLY) approach provided by Springmann et al. [80] and Herrera-Araujo et al. [54]. The justification for using the VSLY approach is that it allows for the estimation of a constant value of life years lost throughout a lifetime (or life expectancy) due to a particular health condition [81,82]. The VSLY is a measure obtained by dividing the value of statistical life (VSL) by a discounted expected number of remaining life years after death to estimate a constant value of life years lost throughout a lifetime (or life expectancy), as shown in Equation (14).

$$\mathrm{VSLY} = \frac{\mathrm{VSL}}{\sum_{t=1}^{n} \frac{1}{(1+r)^{t-n}}} \qquad \text{Equation 14}$$

where n represents the life expectancy in a country, t represents the time of death in years and r is the annual discount rate, usually three per cent [80].

The VSL measures people's willingness to pay for a mortality risk reduction, defined as the marginal rate of substitution between money and mortality risk associated with a health externality in a given time [80]. The VSLY for Kenya (about 5,100 USD) was adopted from Herrera-Araujo et al. [54] and adjusted using a 14.2 % annual CPI inflation rate [77] to obtain 5,824.2 USD equivalent in 2022. The mean dollar value of DALYs (human toxicity from air pollution and health impacts of pesticide exposure) per tonne of green beans across the value chain was estimated, as specified by Equation (15) [54]. The dollar value of DALYs was then multiplied by 69,124 tonnes of green beans produced in 2022 to obtain the total health costs.

$$\text{Dollar value of DALYs}_{\hat{\mu}} = \text{DALYs}_{\hat{\mu}} \text{ x VSLY} \qquad \text{Equation 15}$$

3.7. Uncertainty analysis

Uncertainties in the data used to quantify the negative externalities were accounted for to provide robust results and improve the credibility of the current study [7,83]. Potential sources of uncertainties included the various data, characterisation factors, emission factors and models used to quantify the externalities [3,19]. To account for footprint uncertainty, the central limit theorem was used to estimate the confidence interval (lower and upper bounds) for the mean of each footprint indicator, as specified in Equation (16).

$$\left[\hat{\mu} - 1.96 \cdot \frac{\hat{\sigma}}{\sqrt{n}}, \hat{\mu} + 1.96 \cdot \frac{\hat{\sigma}}{\sqrt{n}}\right] \qquad \text{Equation 16}$$

where $\hat{\mu}, \hat{\sigma}, n$ were the mean, standard deviation and count of the data points for the footprint indicators [7].

The ratios (95 % confidence intervals) $\frac{\hat{\mu}-1.96\cdot\frac{\hat{\sigma}}{\sqrt{n}}}{\hat{\mu}}, \frac{\hat{\mu}+1.96\cdot\frac{\hat{\sigma}}{\sqrt{n}}}{\hat{\mu}}$ were used as relative uncertainty (lower and upper bounds) estimates for each individual footprint indicator [7].

The mean and the lower and upper bound quantities of various footprint indicators were multiplied by their respective monetisation factors from Galgani et al. [7] to account for monetisation uncertainty.

3.8. Limitations and assumptions of the analysis

The scope of the analysis was limited to externalities in the green bean value chain within Kenya and the GHG emissions from air-freighting green beans to Heathrow Airport in the United Kingdom (about 6,817 km). Externalities from the production of fertilisers and pesticides were not considered due to data unavailability. The analysis focused on negative externalities in the value chain, not negating the importance of positive externalities such as carbon sequestration, food security and nutrient cycling [8]. Only negative externalities (costs) which could be compensated, prevented, reduced, restored, or stopped through incentives or sanctions were estimated. Adding positives and negatives would cancel out the important message and actions for addressing the value chain's externalities.

Only the externalities for which data were available were estimated. Data sources included studies for the closest legume value chains, as only a few studies have evaluated externalities in Kenya's green bean value chain. Estimates of some negative environmental externalities depended on the default emission and characterisation factors provided by Basset-Mens et al. [19] and Huijbregts et al. [36]. Green beans repurposed into animal feed were not considered as waste but an income-generating activity as recommended by the Food and Agriculture Organisation of the United Nations [84]. Climate change footprints did not include GHG emissions from green beans used as animal feed. The mean quantities and uncertainties (upper and lower bounds) were not estimated for the land occupation, underage workers and living income gap footprint indicators, as they had only a single data point.

The valuation of externalities was limited to the quantified environmental, health and social impacts for which data were available. As no country and commodity-specific valuation factors were used in estimating environmental and social impacts, uncertainty could still arise from the global monetisation factors provided by Galgani et al. [7]. The global values were adjusted using Kenya's 7.7 % annual CPI inflation rate between 2021 and 2022 to help address this issue. Most remediation costs adopted from Galgani et al. [7] depended on meta-analyses and proxy data, leading to possible underestimation or overestimation of the external costs. Market prices may already incorporate environmental taxes used to compensate for or restore damage and accounting for them in remediation costs may lead to a double costs problem. Finally, monetised health externalities depended on the VSLY for Kenya adopted from Herrera-Araujo et al. [54]. The VSLY values human life, which is often considered priceless and remains a controversial idea for some people [85]. Valuing the loss of life may raise a moral dilemma.

Several assumptions were made in this study. First, it was assumed that the various open-access databases provided quality and reliable data for the study. Second, a typical household was assumed to produce 3.4 tonnes of green beans from one acre of land as most households practise smallholder farming [3]. Third, road transport distances depend on the locations of the farms and packhouses in Kenya. Fresh green beans were assumed to be transported more than 50 km from the farms to packhouses by refrigerated trucks with capacities of 3.5–7.5 tonnes, as recommended by Kleih et al. [3] and Basset-Mens et al. [19].

Fourth, it was assumed that non-market goods, such as air pollution and human health impacts, could be valued despite the inherent difficulty in assigning precise monetary values to these non-tangible goods. Fifth, the abatement costs approach to evaluating externalities could help modify an operation to reduce or eliminate an externality. Sixth, compensation costs expressing the value of the damage caused by an externality could indemnify the affected environmental stocks and people. Seventh, prevention costs could help avoid or avert an externality in future. Eighth, restoration costs could bring environmental quality or people's capabilities to a situation comparable to the original state if technically feasible. Finally, the retribution costs approach to evaluating externalities could express the penalty for violating generally accepted rights, obligations and laws.

4. Results and discussion

This section presents the results and discusses the quantified and monetised negative environmental, health and social externalities in Kenya's green bean value chain. Results were presented as mean estimates of the negative externalities (external costs) and ranges (upper and lower bounds) were specified as confidence intervals for uncertainty estimates.

4.1. Quantified environmental externalities

Table 3 presents the results of the analysed environmental footprints per tonne of fresh green beans in Kenya in 2022. For example, the total GHG emissions from one tonne of green beans amounted to 639 kg CO_2-eq (range 590–688). The production stage accounted for 52.7 % (337 kg CO_2-eq) of the total emissions. This quantity was much higher than the 59 kg CO_2-eq per tonne of tomatoes produced in China [86], possibly due to the intensive use of fertilisers and pesticides in green bean production [3]. It was found that producing green beans on 1 ha of land could emit 2,806.67 kg CO_2-eq, corresponding to 4.44 % of 63,261 kg CO_2-eq agrifood system emissions reported for Kenya in 2021 by FAOSTAT [87]. The packhouse, trade (including transportation to the port of export) and consumption stages within Kenya contributed 19.96 % (128 kg CO_2-eq), 12.76 % (81.5 kg CO_2-eq) and 1.36 % (8.66 kg CO_2-eq), respectively. Food loss and waste accounted for 13.23 % (84.6 kg CO2-eq) of the total emissions, primarily due to the use of green beans rejected for export as compost. These findings indicated that the green bean value chain is carbon-intensive, underscoring the urgent need for stakeholders to abate the value chain's carbon footprint in support of the Government of Kenya's [88] target of reducing national GHG emissions by 32 % by 2030.

The total particulate matter formation was estimated at 1.26 kg $PM_{2.5}$-eq, predominantly from production (45.00 %, 0.56 p.m.$_{2.5}$-eq) and packhouses (35 %, 0.44 p.m.$_{2.5}$-eq). This estimate was almost four times 0.34 p.m.$_{2.5}$-eq from the cabbage value chain in the Netherlands [26]. Green beans in Kenya are primarily grown for export [13], unlike cabbage in the Netherlands. Intensifying green bean production to meet growing global demand increases the use of fertilisers, pesticides and refrigeration, thereby increasing particulate matter emissions [3,15].

The acidification potential per tonne of green beans was estimated at 6.28 SO_2-eq, with production (48.05 %, 3.02 kg SO_2-eq) and packhouses (28.24 %, 1.77 kg SO_2-eq) as major contributors to emissions. This estimate was 1.5 times the 2.42 kg SO_2-eq from one tonne of spinach in Italy [89], possibly due to substantial fertiliser and pesticide use on green bean farms and energy-intensive packhouses. Approximately 2.31 kg NH_3-eq of ammonia emissions were generated from cattle manure (2.16 kg NH_3-eq) and other sources, such as composted green beans and fertilisers (0.152 kg NH_3-eq). The findings underscored the need to keep value chain activities within planetary boundaries, in line with the Government of Kenya's [90] Food Systems and Land Use Action Plan 2024–2030.

Freshwater eutrophication due to phosphorus emission from fertiliser was estimated at 0.41 kg P-eq, with production responsible for 67.53 % (0.28 kg P-eq). Similarly, marine eutrophication due to nitrogen emissions from fertilisers was estimated at 4.9 kg N-eq, mainly from production (84.31 %, 4.13 kg N-eq). Eutrophication was largely attributed to runoff from green bean fields treated with fertilisers, which can harm aquatic life and lower drinking water quality. The results underscored the need for better agricultural nutrient management and pest control strategies, such as avoiding excessive fertiliser and pesticide use to reduce eutrophication.

Scarce blue water use amounted to about 492 m^3, with irrigation at the production stage accounting for 96.62 % (475 m^3) of the total water footprint. This implied that the blue water (32,833,900 m^3) required to produce 69,124 tonnes of green beans in 2022 was 15.64 % of the

Table 3
Environmental footprints per tonne of fresh green beans from production to consumption in Kenya in 2022.

Footprint indicators	Unit	Production (a)	Domestic packhouses (b)	Domestic trade and port (c)	Domestic consumption (d)	Food loss and waste (e)	Total quantities (a+b + c + d + e)	
							Mean quantities	95 % confidence intervals
GHG emissions	kg CO_2-eq	337	128	81.5	8.66	84.6	639	590–688
Terrestrial ecotoxicity	kg 1,4-DB-eq	1.43	0.90	0.68	0.08		3.08	2.35–3.8
Marine ecotoxicity	kg 1.4-DB-eq	14.4	11.2	5.76	0.64		32	15.4–48.6
Particulate matter formation	kg $PM_{2.5}$-eq	0.57	0.44	0.19	0.06		1.26	1.04–1.49
Photochemical oxidant formation (NMVOC emissions)	kg NMVOC	1.85	0.856	0.428	0.214		3.35	3.12–3.59
Photochemical oxidant formation (NOx emissions)	kg NO_x-eq	0.54	0.25	0.12	0.06		0.97	0.90–1.04
Acidification	kg SO_2-eq	3.02	1.77	1.31	0.175		6.28	4.70–7.85
Ozone layer-depleting emissions	kg CFC11-eq	0.000046	0.0000049	0.0000025	0.0000013		0.000055	0.000047–0.000063
Ammonia emissions	kg NH_3-eq	2.31					2.31	2.20–2.51
Freshwater eutrophication	kg P-eq	0.28	0.08	0.05	0.007		0.41	0.28–0.54
Marine eutrophication	kg N-eq	4.13	0.53	0.18	0.06		4.90	3.32–6.48
Freshwater ecotoxicity	kg 1.4-DB-eq	29.50					29.50	21.2–37.8
Land occupation by green beans	MSA*ha*yr	0.000011					0.000011	N/A
Land transformation	MSA*ha	0.00000051					0.00000051	0.00000047–0.00000054
Scarce blue water use	m^3	475	14.7		1.9		492	479–504
Soil organic carbon (SOC) loss	kg SOC	70					70	39.5–101

Source: Authors' calculations.

210,000,000 m^3 used to irrigate all crops in Kenya based on the statistics from the United Nations Environment Programme [91]. The findings suggested that farmers need to adopt water-efficient drip irrigation systems to reduce scarce blue water use. The packhouse and consumption stages contributed only 2.99 % (14.7 m^3) and 0.39 % (1.9 m^3), respectively.

Fig. 2 presents the percentage distribution of environmental footprints per tonne of green beans across the value chain stages. The farm production stage had more environmental externalities, representing at least 45 % of any ecological footprint. This finding corroborated the results of Impact Institute [43] and Bergman et al. [41], who noted that the environmental footprints of food value chains were higher at the production stage than at other stages. The packhouse stage was the second contributor to ecological footprints, followed by trade. The consumption stage contributed the least as the green bean value chain is primarily for export.

In addition to the environmental footprint within Kenya, 8,383.33 kg CO_2-eq (range 7,769.87–8,996.79) were emitted from air-freighting one tonne of green beans from Kenya (Jomo Kenyatta International Airport) to the United Kingdom (Heathrow Airport). The GHG emissions corresponded to 13.25 % of 63,261 kg CO_2-eq agrifood system emissions reported for Kenya in 2021 by FAOSTAT [87]. The results indicated that GHG emissions from air-freighted fresh green beans (8,383.33 kg CO_2-eq) were at least thirteen times as high as domestic emissions (639 kg CO_2-eq). Air-freighting one tonne of green beans can increase the total GHG emissions from the wider export value chain (farm to the importing country) to 9,022.33 kg CO_2-eq (range 8,359.87–9684.79). These findings indicated that GHG emissions from air-freighting fresh green beans spread outside Kenya's boundaries, creating regional or global climate change concerns. Additionally, the findings underscored the need for carbon capture and storage technology in cargo planes to reduce GHG emissions.

4.2. Quantified health externalities

On average, health externalities across the value chain stages were estimated at 0.0024 DALYs per tonne of green beans. This estimate comprised human toxicity from air pollution (0.000048 DALYs, range 0.000029–0.000067) and health impacts from pesticide exposure (0.00235 DALYs, range 0.0014–0.0033). Compared to a study by Perotti [70] that estimated 0.00026 DALYs per tonne of carrots in Switzerland, the health externalities of green beans were at least nine times higher than those of carrots. Kenya's export-oriented green bean value chain relies more heavily on fertilisers, pesticides, irrigation and refrigeration than Switzerland's domestic carrot value chain [3,70,92], leading to substantial health externalities.

Although the burden of mortality and morbidity was low per tonne of green beans, these impacts could accumulate and become significant when 65,124 tonnes of green beans produced in 2022 were considered (about 165.90 DALYs). While consumers in Europe and the United Kingdom demand affordable green beans [15], the current green bean value chain poses a threat to people's health in Kenya. The findings highlighted the need for strategies to mitigate the health impacts of the green bean value chain, thereby contributing to the Government of Kenya's [93] vision of improved human health by 2030.

4.3. Quantified social externalities

Table 4 presents the quantified social externalities of producing one tonne of green beans in Kenya in 2022. The presence of almost 224 underage workers (over 179 children aged 5–12 years, plus 44 children aged 13–15 years) involved in more than 800 hours per week raised ethical and social concerns. If these children worked at least one hour per week (5–12 years) and 14 hours (13–15 years) in non-hazardous conditions, a total of 0.000285 child FTEs was estimated per tonne of green beans. About five children aged 16–17 years, each working 42 hours per week in hazardous conditions, contributed to roughly 0.000076 child FTEs per tonne of green beans. Therefore, a total of

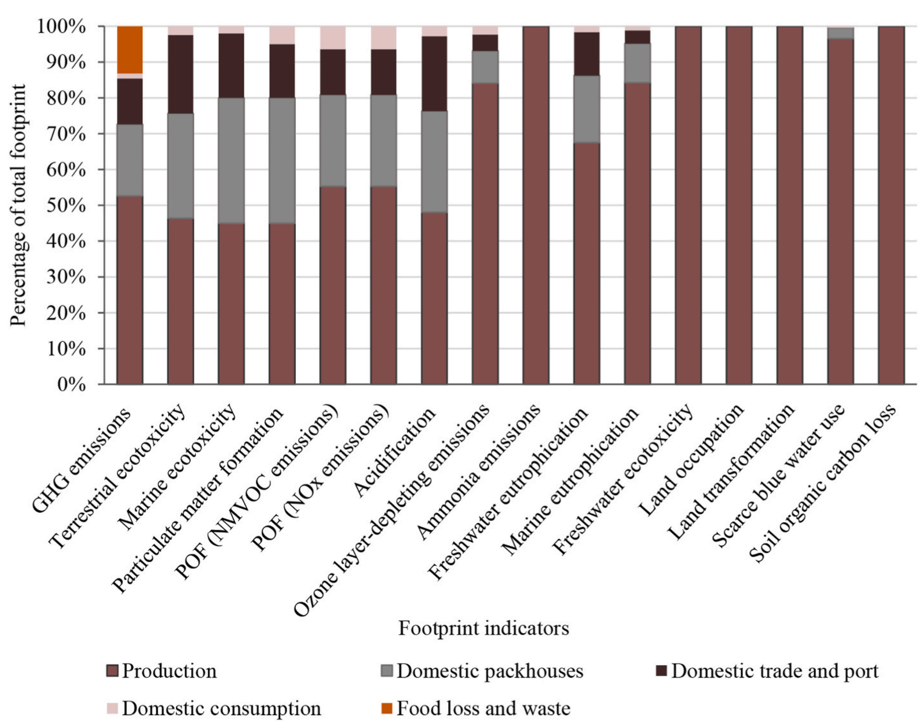

Fig. 2. Contribution of value chain stages to environmental footprints per tonne of green beans. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors' work.

Table 4
Social footprints per tonne of green beans in Kenya's value chain in 2022.

Footprint indicators	Unit	Number of underage workers in the production of all green beans	Minimum hours worked per week	Total hours worked per week	Quantities per tonne of green beans
Underage workers (5–12 years) in non-hazardous work	Child FTE	179.25	1	179.25	0.000065
Underage workers (13–15 years) in non-hazardous and non-light work	Child FTE	44.36	14	620.97	0.00022
Underage workers (16–17 years) in hazardous work	Child FTE	5.03	42	211.26	0.000076
Underage workers not attending school	Children	29.04	Not applicable (N/A)	N/A	0.00042
Living income gap	US dollar	N/A	N/A	N/A	740

Note: One full-time equivalent (FTE) = a full-time job of 40 h per week. Household's net income from all green beans = 493.08 USD and living income benchmark = 2,997.13 USD.
Source: Authors' calculations.

0.00036 child FTEs was estimated for underage workers involved in hazardous and non-hazardous working conditions.

Although 0.00036 child FTEs per tonne of green beans appeared minimal, the cumulative impact of child labour was substantial, considering 69,124 tonnes produced in 2022. Based on this premise, 24.88 child FTEs (almost 1012 labour hours) were estimated in the value chain. Further, about 29 underage workers across the value chain (0.00042 children per tonne of green beans) were not attending school, underscoring the negative impact of agricultural child labour on education.

The living income gap was quantified as about 740 USD per tonne of green beans, indicating that a household's annual net earnings from green bean production were insufficient to meet the cost of a basic but decent living standard. This living income gap was almost twice as high as the average farmgate price (420 USD) of green beans in Kenya. It was more prominent when about 3.4 tonnes of green beans produced by a household practising small-scale farming were considered (2,516 USD). Further, the estimated household's annual net gross earnings (493.08 USD) from 3.4 tonnes of green beans were only 16.45 % of the living income benchmark (2,997.13 USD). These findings highlighted the need for pricing models that guarantee fair floor prices for agricultural inputs and green beans (farmgate prices) in Kenya.

4.4. *Monetised environmental externalities*

Table 5 presents the monetised environmental footprints per tonne of fresh green beans from production to consumption in Kenya in 2022. For example, the costs of scarce blue water use were estimated at 788.89 USD per tonne of green beans, contributing the highest (57.71 %) to the total average external costs (1367.10 USD) across the value chain. The results implied that the costs of scarce blue water use were almost half the average export price of one tonne of green beans (2,171 USD). The costs (10.82 USD) of blue water use per tonne of Kenya's coffee in 2022 [43] were only 1.37 % of the water use costs of one tonne of green beans (1 USD = 0.9239 EUR), as green bean production is highly water-intensive (475 m^3 of water). The findings underscored the need for strategies to reduce or compensate for blue water withdrawals by value chain stakeholders, especially farmers and packhouse operators.

GHG emissions had the second-highest external costs (154.18 USD) per tonne of green beans, accounting for 11.28 % of the total average external costs across the value chain. This hidden cost was about 7.1 % of the export price of one tonne of Kenya's green beans. In addition, the estimated 154.18 USD for GHG emissions per tonne of green beans was at least twice as high as 64.94 USD for Kenya's coffee in 2022, based on estimates by the Impact Institute [43]. The green bean value chain generated substantial GHG emissions (639 kg CO_2-eq, range 590–688)

Table 5
Monetised environmental footprints in US dollars per tonne of fresh green beans across the value chain in Kenya in 2022.

Footprint indicators	Production (a)	Domestic packhouses (b)	Domestic trade and port (c)	Domestic consumption (d)	Food loss and waste (e)	Total external costs per indicator (a+b + c + d + e)	
						Mean external costs	95 % confidence intervals
GHG emissions	81.25	30.77	19.67	2.09	20.40	154.18	142.34–166.02
Terrestrial ecotoxicity	0.0006	0.0004	0.0003	0.00003		0.0013	0.001–0.0016
Marine ecotoxicity	0.04	0.03	0.02	0.002		0.09	0.04–0.14
Particulate matter formation	45.95	35.74	15.32	5.11		102.12	83.73–120.51
Photochemical oxidant formation from NMVOC emissions	2.36	1.09	0.54	0.27		4.26	3.96–4.56
Photochemical oxidant formation from NO_x emissions	2.43	1.12	0.56	0.28		4.39	4.08–4.70
Acidification	21.76	12.79	9.47	1.26		45.28	33.90–56.67
Ozone layer-depleting emissions	0.0033	0.00035	0.00018	0.000089		0.0039	0.0033–0.0044
Ammonia emissions	28.64					28.64	27.46–30.78
Freshwater eutrophication	86.40	23.89	15.58	2.08		127.95	87.29–168.62
Marine eutrophication	89.51	11.50	3.96	1.19		106.16	71.97–140.36
Freshwater ecotoxicity	1.84					1.84	1.32–2.36
Land occupation by green beans	0.04					0.04	0.04–0.04
Land transformation	0.00017					0.00017	0.00016–0.00018
Scarce blue water use	762.25	23.59		3.05		788.89	768.65–809.12
Soil organic carbon loss	3.24					3.24	1.83–4.66
Total average external costs across the value chain stages						**1,367.10**	

Note: As land occupation had no uncertainty estimates, its monetised mean value (0.04 USD) was used as the lower and upper bounds.
Source: Authors' calculations.

from fertilisers, pesticides, diesel-powered water pumps, refrigerated trucks and cold rooms, resulting in higher external costs than the coffee value chain. The production (81.25 USD) and packhouse (30.77 USD) stages contributed the most to the GHG emission-related external costs, as they had high emission quantities. The external costs of GHG emissions from food loss and waste were roughly 20.40 USD. The results highlighted the need to address activities across the value chain that cause GHG emissions, including food loss and waste, to support Kenya's target of a 32 % reduction in national emissions by 2030.

Freshwater and marine eutrophication accounted for 5.89 % and 4.89 % of the average export price (2171 USD) of one tonne of green beans, respectively. One tonne of green beans generated freshwater eutrophication, amounting to 127.95 USD. This value comprised costs from the production (86.40 USD), packhouse (23.89 USD), trade (15.58 USD) and consumption (2.08 USD) stages. Marine eutrophication accrued external costs of 106.16 USD, comprising 89.51 USD from production, 11.50 USD from packhouses, 3.96 USD from trade and 1.19 USD from consumption. The external costs of marine eutrophication per tonne of Kenya's green beans were at least three times as high as 31 USD reported for one tonne of carrots in Switzerland (1 USD = 0.9590 Swiss francs) by Perotti [70]. The high eutrophication costs were largely attributed to fertiliser-intensive green bean production and runoff from green bean fields treated with fertilisers. The results indicated the need to reduce eutrophication across the green bean value chain and address damage to aquatic life and water quality deterioration as required by Kenya's Water Act, 2016.

The total costs of particulate matter formation were 102.12 USD, accounting for 7.74 % of the total average external costs (1,367.10 USD) across the value chain. The production (45.95 USD) and packhouse (35.74 USD) stages substantially contributed to particulate matter formation. These costs were driven by particulate matter emissions from fertilisers, pesticides, refrigerated trucks and energy used to operate cold rooms.

The valuation process revealed 45.28 USD per tonne of green beans for acidification, representing 3.31 % of the total average external costs. The farm production stage largely created this external cost due to many activities emitting air pollutants with acidification potential. The estimated hidden costs of acidification per tonne of green beans were more than four times higher than those derived by Perotti [70] for one tonne of carrot (10 USD) in Switzerland. The high sulphur dioxide emissions (6.28 SO_2-eq) from fertilisers, pesticides and energy-intensive packhouses created substantial acidification costs in the green bean value chain. Ammonia emissions amounted to 28.64 USD, originating entirely from the production stage and accounting for 2.09 % of the total average external costs. This hidden cost represented 6.82 % of the average farmgate price of one tonne of green beans (420 USD) in Kenya. Although these costs were low per tonne of green beans, their magnitude could rise with an increased quantity of green beans across the value chain.

The results discussed in the preceding paragraphs relate to a functional unit of one tonne of fresh green beans, not the entire volume across the value chain. These external costs were multiplied by the quantity of green beans allocated to each value chain stage (Table 2 in Section 3.5 provided the allocations) to obtain the external costs for all green beans in 2022 (see Supplementary Table 3). For example, the scarce blue water footprint indicator still had the highest external costs at 53.77 million USD, accounting for 61.89 % of the total average external costs (86.87 million USD) across the value chain. This hidden cost almost equalled the 53.92 million USD market value of 69,124 tonnes of green beans produced in Kenya in 2022. It was nearly twice the farmgate value (29.03 million USD) of all green beans and slightly higher than the export value (42.15 million USD) of 19,417 tonnes of green beans exported in 2022. These imbalances suggest that without strategies to reduce or compensate for water withdrawals by farmers and packhouses, external costs will increase as green bean production expands and intensifies to meet the growing global demand for the produce.

GHG emissions totalled 8.04 million USD, mainly from the production (5.62 million USD) and packhouse (1.34 million USD) stages. This external cost (8.04 million USD) accounted for 27.68 % of the total farmgate value, 14.91 % of the total market value and 19.07 % of the total export value of green beans. The external costs of GHG emissions from all green beans in Kenya were two times higher than the 3.74 million USD estimated by White [94] for Malawi's maize value chain. Malawi's maize production for both domestic use and export is predominantly rain-fed and less input-intensive (White, 2019), resulting in low GHG emissions and associated external costs. Kenya could fail to achieve its ambition of reducing national GHG emissions by 32 % by 2030 if the green bean value chain's carbon footprint is not abated.

The external costs of freshwater and marine eutrophication amounted to 7.61 and 6.85 million USD, collectively accounting for 16.65 % of the total average external costs across the value chain. These costs mainly accrued at the production and packhouse stages due to the high emission of phosphorus and nitrogen from fertilisers and waste into water bodies. Eutrophication costs accounted for 49.8 % of the total farmgate value, 26.82 % of the total market value and 34.3 % of the total export value of green beans, indicating a serious threat to aquatic life and a high cost of water quality restoration. The particulate matter formation was estimated at 5.37 million USD, accounting for 6.18 % of the total average external costs (86.87 million USD). Particulate matter formation costs were high at the farm stage (3.18 million USD) and lowest at the consumption stage (84,602.71 USD). For acidification, the external costs summed up to 2.42 million USD, representing 2.79 % of the total average external costs (86.87 million USD). Ammonia emissions were approximately 1.98 million USD (2.28 %), accrued at the production stage due to manure use.

The estimated external costs of footprint indicators that measure a common externality, such as air, soil and water pollution, were summed up to calculate the costs associated with that externality. Table 6 presents the monetised environmental externalities of the fresh green bean value chain. Air pollution was evaluated based on the external costs of acidification, ammonia emissions, ecotoxicity, ozone layer-depleting emissions, particulate matter formation and photochemical oxidant formation. The external costs of air pollution from one tonne of green beans were estimated at 184.79 USD (13.25 %), accounting for 44 % of the average farmgate price, 23.7 % of the market price and 8.5 % of the export price. This finding was similar to a 13 % contribution of air pollution to the total environmental costs of one tonne of Kenya's coffee in 2022 [43], as the green bean and coffee value chains generate substantial air pollutants from fertilisers and pesticides. Further, air pollution accrued 10.25 million USD (11.8 %) for all green beans across the value chain. This cost represented 26 % of 40 million USD associated with air pollution in Nairobi in 2023 [95], necessitating stakeholder actions that adhere to the Air Quality Regulations, 2014, specified by the Government of Kenya [96].

Water pollution had external costs of 234.12 USD (17.13 %) per tonne of green beans and 14.46 million USD (16.64 %) for all green beans across the value chain. This external cost (0.234 USD) was even higher than the external cost of water pollution per tonne of Kenya's green leaf tea (169 USD) in 2015 (1 USD = 0.912 EUR), as reported by Bergman et al. [41]. This finding was attributed to the proximity of green bean farms to water bodies and runoff from green bean fields treated with fertilisers. The external costs of water pollution for all green beans (14.46 million USD) represented 49.8 % of its farmgate value, 26.82 % of the market value and 34.3 % of the export value. These costs represented the abatement costs of reducing water pollution, as well as the costs of compensating for the economic damage and biodiversity loss caused by water pollution. Soil pollution generated external costs of about 1.8 USD (0.13 %) per tonne of green beans and 127,164.89 USD (0.15 %) for all green beans.

Overall, the total cost of negative environmental externalities amounted to 1367.10 USD (range 1226.62–1508.52) per tonne of green

Table 6
Monetised environmental externalities in Kenya's fresh green bean value chain in 2022 (US dollars).

Externalities/impacts	Total external costs per tonne of green beans across the value chain		Total external costs for all green beans across the value chain	
	Mean external costs	95 % confidence intervals	Mean external costs	95 % confidence intervals
Contribution to climate change	154.18	142.34–166.02	8,036,751.67	7,490,748.55–8,582,754.79
Air pollution	184.79	153.18–217.36	10,252,541.54	8,532,879.47–12,038,339.84
Water pollution	234.12	159.26–308.97	14,458,827.47	10,295,989.56–18,621,665.38
Soil pollution	1.84	1.30–2.40	127,164.89	91,270.20–163,059.59
Land occupation by green beans	0.04	0.04–0.04	2752.76	2752.76–2752.76
Land transformation	0.00017	0.00016–0.00018	11.79	10.93–12.65
Scarce blue water use	788.89	768.65–809.12	53,767,339.63	52,619,571.28–54,915,107.98
Soil degradation due to soil organic carbon loss	3.24	1.83–4.66	224,084.11	126,343.70–321,824.52
Total external costs across the value chain stages	**1,367.10**	**1,226.62–1508.52**	**86,869,473.86**	**79,159,566.44–94,645,517.51**
Farmgate price or value of green beans (US dollars)	420.00	N/A	29,032,080.00	N/A
Market price or value of green beans (US dollars)	780.00	N/A	53,916,720.00	N/A
Export price or value of green beans (US dollars)	2,171.00	N/A	42,154,307.00	N/A

Note: As land occupation had no uncertainty estimates, its monetised mean value was used as the lower and upper bounds.
Source: Authors' calculations.

beans. The environmental costs were at least three times the average farmgate price (420 USD) and almost twice the average market price (780 USD) of one tonne of green beans. They accounted for 62.97 % of the average export price of 2171 USD per tonne of green beans. The results corroborated the findings of the Impact Institute [43], which reported similar environmental costs (1578.14 USD) for one tonne of coffee in Kenya in 2022. The findings of this study underscored the critical need to reduce negative environmental externalities in Kenya's green bean value chain.

Fig. 3 compares the total environmental costs across different stages of Kenya's green bean value chain in 2022. On average, the total environmental costs across the value chain were approximately 86.87 million USD (range 79.16–94.65). These costs were almost three times as high as the farmgate value of all green beans (29.03 million USD), at least 1.6 times its market value (53.92 million USD) and twice the export value (42.15 million USD). The environmental costs were highest at the production stage (77,814,915.66 USD, 89.58 %) due to more externalities, followed by packhouses at about 6,119,271.26 USD (7.04 %). The costs of negative environmental externalities of farm production were nearly three times the farmgate value of all green beans and almost twice its export value. Domestic trade and consumption accounted for 2.7 % (2,343,361.46 USD) and 0.29 % (253,960.88 USD) of the total environmental costs, respectively. Food loss and waste contributed 337,964.61 USD, representing 0.39 % of the total ecological costs. The findings were in line with previous studies on the true costs of food value chains, which reported production-related environmental costs to be higher than other value chain stages [41,43]. Moreover, the findings indicated that the ecological costs are not accounted for in the current farmgate and export prices of green beans.

Considering the environmental costs per tonne of air-freighted fresh green beans to the United Kingdom, the external costs of GHG emissions amounted to 2022.46 USD (range 1,874.47–2,170.46). This hidden cost almost equalled the export price of one tonne of green beans (2171 USD). On average, total external costs related to climate change through GHG emissions increased from 154.18 USD (domestic costs) to 2,176.64 USD, including air-freight costs. Further, GHG emission external costs totalled 39.27 million USD (range 36.40–42.14) for 19,417 tonnes of green beans exported in 2022 (Table 7). This external cost was almost

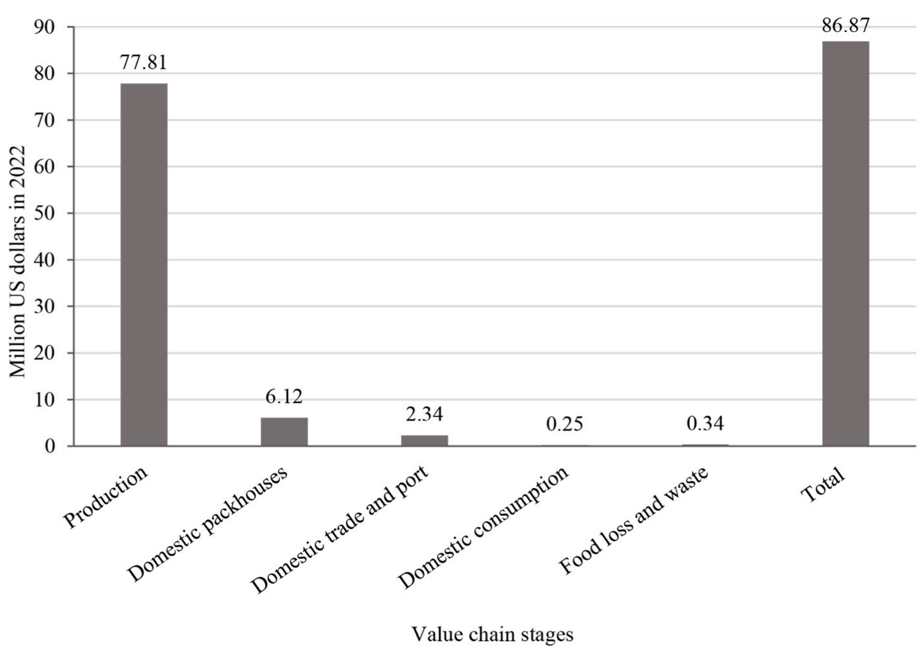

Fig. 3. Distribution of monetised environmental externalities (USD) across Kenya's green bean value chain in 2022.
Source: Authors' work.

Table 7
Comparison of external costs of in-country GHG emissions with air-freighting emissions (US dollars) from all green beans in 2022.

Description of GHG emissions	Mean external costs	95 % confidence intervals
From the farm to Jomo Kenyatta International Airport (domestic or within Kenya)	8,036,751.67	7,490,748.55–8,582,754.79
From Jomo Kenyatta International Airport (Kenya) to Heathrow Airport (United Kingdom)—air-freighting GHG emission costs	39,270,152.42	36,396,508.98–42,143,795.86
Total external costs of GHG emissions	47,306,904.09	43,887,257.53–50,726,550.65
Total in-country environmental costs	86,869,473.86	79,159,566.44–94,645,517.51
Total in-country environmental costs plus air-freighting GHG emission costs	126,139,626.28	115,556,075.42–136,789,313.37

Source: Authors' calculations.

five times as high as the in-country external costs of GHG emissions from all green beans (8.04 million USD). It comprised 93.16 % of the total export value of green beans in 2022 (42.15 million USD). Therefore, including all air-freighted green beans in the valuation can increase the total external costs of GHG emissions from 8.04 to 47.31 million USD and environmental costs from 86.87 to 126.14 million USD.

4.5. *Monetised health externalities*

On average, the dollar value of health-related DALYs was roughly 13.98 USD (range 8.33–19.63) per tonne of green beans, as shown in Table 8. This estimate implied that 3.33 % (range 1.98–4.67 %) was surcharged on the average farmgate price (420 USD) of one tonne of green beans due to health externalities. The results of this study revealed that health costs (13.98 USD) accounted for about 14.77 % of the World Bank's 94.67 USD current per capita health spending in Kenya in 2021 [77]. This finding indicated that health externalities in Kenya's green bean value chain exert a non-trivial burden on people's health expenditure. The drivers of the health costs included human toxicity from air pollution caused by agrochemicals (fertilisers and pesticides) and the health impacts of pesticide exposure. The estimated health costs could rise as the volume of green beans in Kenya increases.

Considering the entire quantity of green beans (69,124 tonnes) produced in 2022, the cost of health impacts amounted to 0.97 million USD (range 0.58–1.36). This estimate represented 3.33 % of the total farmgate value, 1.79 % of the total market value and 2.29 % of the total export value of green beans in Kenya. In addition, this estimate accounted for 0.02 % of Kenya's health expenditure (5.01 billion USD) in 2021 [77]. The total health costs for the green bean value chain were 1.5 times the external costs of pesticide exposure (0.65 million USD) estimated by Macharia [28] for Kenya's vegetable sub-sector (cabbage, kale and potato) between 2003 and 2008. The results indicated that the negative health impacts of the green bean value chain were evident and measurable, underscoring the need for stakeholders to mitigate these externalities.

4.6. *Monetised social externalities*

Table 9 presents the monetised social externalities of Kenya's green bean value chain in 2022. The results showed that about 179 underage workers of 5–12 years working for a minimum of one hour per week in non-hazardous conditions had total external costs of 1.5 USD per tonne of green beans. This estimate accounted for 28.3 % of the total external costs of underage workers in the value chain (5.3 USD). External costs associated with this age set (5–12 years) increased to at least 104,248.51 USD, considering the entire quantity of green beans (69,124 tonnes) produced in 2022. This external cost was equivalent to the sum of the living income benchmark (cost of a basic but decent living standard) for almost 35 green bean farm households in 2022 (Kenya's household living income benchmark = 2,997.13 USD).

The results revealed that at least 44 (13–15 years) and five (16–17 years) underage workers working for a minimum of 14 and 42 h per week had total external costs of 1.9 USD per tonne of green beans per age set. This estimate implied that each age set represented 35.85 % of the total external costs of underage workers in the value chain. Further, the results revealed higher external costs of underage workers of 13–15 years (133,256.41 USD) and 16–17 years (130,827.74 USD) when all green beans produced in 2022 were factored in. The total external costs of underage workers within 13–17 years (264,084.15 USD) were equivalent to the sum of living income benchmark of at least 88 green bean farm households in 2022.

For the underage workers not attending school (at least 29 in number), the external cost amounted to approximately 11.40 USD per tonne of green beans, compared to 40 USD estimated by the Impact Institute [43] for one tonne of Kenya's coffee in 2022. This estimate (11.40 USD) implied that 2.7 % was surcharged on the average farmgate price (420 USD) and 1.5 % on the average market price (780 USD) of one tonne of green beans due to underage workers not attending school. Considering all green beans produced in 2022, the external costs of underage workers not attending school amounted to about 0.79 million USD, equivalent to 0.02 % of 5.22 billion USD expenditure by the Kenyan government on education in 2021 [77]. This external cost corresponded to a combined nominal gross domestic product (GDP) per capita of about 377 people and a living income benchmark of roughly 264 green bean farm households in Kenya in 2022. Kenya's nominal GDP per capita in 2022 was 2,099.30 USD [77].

A sum of the external costs of underage workers (5–17 years) involved in hazardous and non-hazardous work and those not attending school provided child labour costs of about 16.7 USD per tonne of green beans. This estimate accounted for about four per cent of the farmgate

Table 8
Monetised health externalities in Kenya's green bean value chain in 2022 (US dollars).

Health externalities	Total external costs/tonne of green beans		Total external costs for all green beans	
	Mean	95 % confidence intervals	Mean	95 % confidence intervals
Human toxicity from air pollution	0.28	0.17–0.39	19,324.42	11,512.92–27,135.91
Health impacts from pesticide exposure	13.70	8.16–19.24	946,896.39	564,133.05–1,329,659.72
Total health costs	**13.98**	**8.33–19.63**	**966,220.80**	**575,645.97–1,356,795.63**
Farmgate price or value of green beans (US dollars)	420.00	N/A	29,032,080.00	N/A
Market price or value of green beans (US dollars)	780.00	N/A	53,916,720.00	N/A
Export price or value of green beans (US dollars)	2,171.00	N/A	42,154,307.00	N/A

Source: Authors' calculations.

Table 9
Monetised social externalities (US dollars) of the green bean value chain in Kenya in 2022.

Social externalities	Social footprint indicators	Number of underage workers	Minimum hours worked per week	External costs per tonne of green beans	External costs for all green beans
Child labour	Underage workers (5–12 years) in non-hazardous economic work	179.25	1	1.50	104,248.51
	Underage workers (13–15 years) in non-hazardous and non-light economic work	44.36	14	1.90	133,256.41
	Underage workers (16–17 years) in hazardous work	5.03	42	1.90	130,827.74
	Underage workers not attending school	29.04	N/A	11.40	791,196.33
	Total external costs of child labour	**N/A**	**N/A**	**16.70**	**1,159,528.99**
Insufficient income	Living income gap	N/A	N/A	844.80	35,037,523.35
Total social costs	**N/A**	**N/A**	**N/A**	**861.50**	**36,197,052.34**

Source: Authors' calculations.

price and almost two per cent of the total social external costs of one tonne of green beans. The results of this study were similar to the findings of Impact Institute [43], which noted that child labour-related external costs of one tonne of Kenya's coffee represented three per cent of its total social costs in 2022. Accounting for the entire quantity of green beans (69,124 tonnes) produced in 2022, external costs of child labour amounted to about 1.16 million USD. This external cost estimate was equivalent to a combined nominal GDP per capita of at least 552 people in 2022 [77]. The results for underage workers (5–17 years) in various work conditions and those not attending school revealed substantial external costs with the potential to limit the future opportunities of children.

The living income gap (insufficient income) estimated external cost of 844.80 USD per tonne of green beans was at least twice as high as its average farmgate price (420 USD). A household producing 3.4 tonnes of green beans on one acre of land and earning annual gross revenue of 1,443.86 USD at the farmgate price accrued external costs of at least 2872.32 USD, almost twice as big as the earned gross revenue. The estimated living income gap-related costs of 844.80 USD per tonne of green beans were slightly higher than 670 USD, reported by Impact Institute (2023) for one tonne of Kenya's coffee in 2022. This cost (844.80 USD) was also at least three times the 250 USD living income gap costs per tonne of Kenya's roses (25,000 rose stems = one tonne) in 2020 [42]. The estimated external cost exceeded the market price of one tonne of green beans (780 USD) and accounted for 38.91 % of its export price (2,171 USD).

Considering 41,474 tonnes (60 % of 69,124 tonnes) of green beans produced by smallholder farmers in 2022, the living income gap-related external cost was roughly 35.04 million USD. This cost was equivalent to a sum of the GDP per capita of 16,910 individuals and it could be enough to meet the money requirements of 11,690 households for their basic but decent living standards. In addition, the external cost estimate represented at least 0.2 % of about 22.68 billion USD contributed by agriculture to Kenya's nominal GDP in 2022 [77,97]. The findings implied that a household's annual net earnings from green bean production were insufficient to meet its cost of a basic but decent living standard. Many farm households may have resorted to family labour, including child labour, due to insufficient income. There is a need for fair pricing to improve farmers' earnings and living standards.

Overall, the estimated total cost of negative social externalities was 861.50 USD per tonne of green beans (a sum of the external costs of child labour and insufficient income). This estimate was at least twice as high as the farmgate price of one tonne of green beans (420 USD), 81.50 USD above its market price (780 USD) and 39.68 % of its export price (2171 USD). In addition, this external cost estimate (861.50 USD) almost equalled the 930 USD social costs of one tonne of Kenya's green leaf tea in 2015 (1 USD = 0.912 EUR) based on a study by Bergman et al. [41]. Further, the social costs per tonne of green beans nearly equalled 975 USD, estimated by Impact Institute [42] for one tonne of Kenya's roses in 2020, considering gender discrimination, lack of social security and poor health and safety. The findings implied that the social costs of the green bean value chain could exceed those of the rose value chain if additional social externalities were estimated for green beans.

The social costs amounted to approximately 36.20 million USD for all the green beans produced in Kenya in 2022. This estimate was equivalent to the sum of the GDP per capita of about 17,242 individuals. It could be enough to meet the money requirements of about 12,077 households for their basic but decent living standards. The estimated total social cost was higher than the total farmgate value of all green beans (29.03 million USD). Social costs accounted for 67.14 % of the total market value (53.92 million USD) and 85.87 % of the total export value (42.15 million USD) of all green beans.

4.7. Aggregate value of monetised environmental, health and social externalities

A sum of the estimated environmental, health and social costs provided the total external costs for the value chain, first for one tonne of green beans (functional unit) and then for all green beans. Fig. 4 shows that on top of the average market price of 780 USD, the external costs per tonne of green beans amounted to 2,242.58 USD (range 2,096.45–2,389.65). The drivers of these external costs were environmental costs (1,367.10 USD, 60.96 %), health costs (13.98 USD, 0.62 %) and social costs (861.50 USD, 38.42 %). The findings showed that the external costs of one tonne of green beans were almost three times its average market price (780 USD). This implication corroborated the findings of Bergman et al. [41], who noted that the external costs (1,210 USD) per tonne of Kenya's green leaf tea in 2015 were at least three times its market price (380 USD).

The average export price of one tonne of green beans (2,171 USD) nearly equalled its estimated total external costs (2,242.58 USD). The export price per tonne of green beans was higher than its market price, possibly justifying why the external cost was almost the same as the export price but at least three times the market price (Fig. 4). However, those benefiting from higher export prices of green beans are the exporters (usually large-scale producers or packhouse operators), while smallholder farmers receive low farmgate prices.

The total external costs (2,242.58 USD) per tonne of green beans were higher than the average export price (2,171 USD), indicating that the costs of environmental, health and social externalities in Kenya's green bean value chain are not accounted for in the current export price of green beans. Consumers in Europe and the United Kingdom are budget-constrained and price-conscious, demanding affordable, fresh green beans [15]. In 2022, the average retail price of 1 kg of fresh green

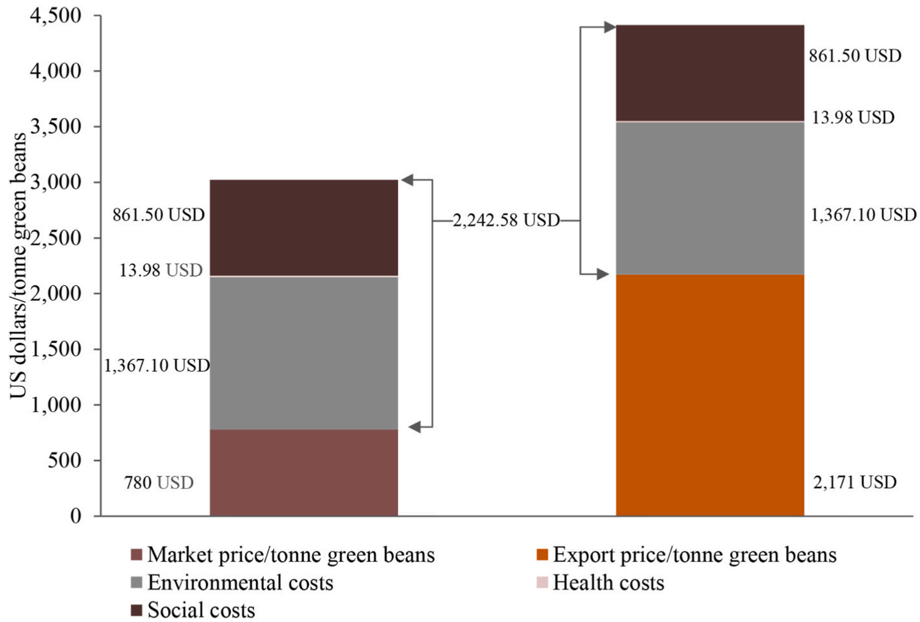

Fig. 4. Estimate of the total external costs (US dollars) per tonne of green beans across the value chain in Kenya in 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors' work.

beans in Europe was 4.33 USD (1 USD = 0.9239 EUR), equivalent to 4, 330 USD per tonne of green beans [15]. Considering all possible gross margins (net income) of farmers, packhouse operators, distributors and traders, it is clear that the retail price of 4,330 USD per tonne of fresh green beans in Europe did not account for the costs of negative externalities (2,242.58 USD) in Kenya's green bean value chain. The findings underscored the need for value chain stakeholders to internalise the hidden costs without making the produce unaffordable for consumers.

Considering all the green beans produced in 2022, the total costs of negative externalities in the value chain were estimated at 124.03 million USD (range 115.93–132.20). These costs comprised about 86.87 million USD (range 79.16–94.65) in environmental costs, 0.97 million USD (range 0.58–1.36) in health costs and 36.20 million USD in social costs (Fig. 5). The environmental costs were the highest due to more ecological externalities, followed by social and health costs. The total external costs were at least twice as high as the 53.92 million USD market value of all green beans in Kenya. In addition, the total external costs were almost three times the export value of all green beans (42.15 million USD), driven by substantial externalities relative to the smaller export volume in 2022 (19,417 tonnes). Further, the total external costs were equivalent to the sum of the nominal GDP per capita of at least 59,083 people and the money required by 41,384 farm households in

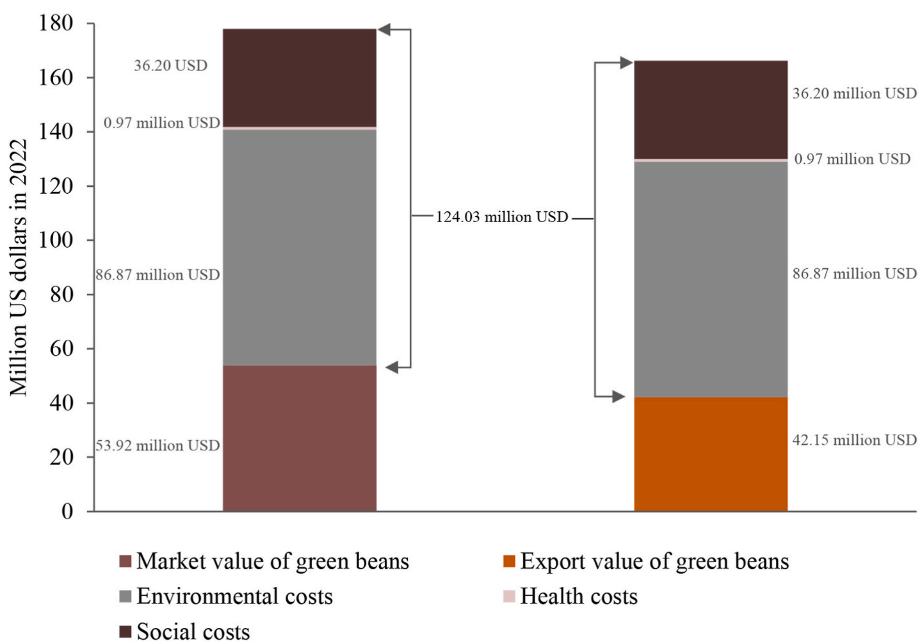

Fig. 5. Estimate of the total external costs (US dollars) of all green beans across the value chain in Kenya in 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors' work.

Kenya to meet their basic but decent living standards. The findings of this study were in line with assertions made in other studies on the true costs of food systems. Annual global estimates in 2021 indicated that negative externalities in food system were twice as high as the amount spent on purchasing food [8]. A parallel estimation by the FAO [9] indicated that annual global food systems externalities were almost twice the amount spent on purchasing food.

Considering the in-country (1,367.10 USD) and air-freight (2,022.46 USD) environmental costs of one tonne of green beans, the total external costs increased from 2242.58 USD to 4,265.04 USD (range 3,970.92–4,560.11). The total external costs (4,265.04 USD) were at least five times as high as the average market price of one tonne of green beans (780 USD) and almost twice the average export price (2171 USD). Including the environmental costs of air freight, the retail price of 4,330 USD per tonne of fresh green beans was insufficient to cover various gross margins and external costs (4,265.04 USD) of green beans imported from Kenya. Although some consumers could be willing to pay premium prices for sustainably sourced green beans [15], higher prices could exclude poorer consumer segments. There is a need for the value chain transformation by encouraging stakeholders to be accountable and responsible for the hidden costs (negative externalities).

Moreover, the total external costs of all green beans amounted to 163.30 million USD (range 152.33–174.34), including air-freighting environmental costs (see Supplementary Table 4). The external costs were three times as high as the market value of all green beans (53.92 million USD) and almost four times its export value (42.15 million USD). The results indicated that GHG emissions from air-freighting green beans contributed substantially to total external costs, underscoring the need for mandatory carbon capture and storage technology in cargo planes and enforcement of carbon taxes, as recommended by Garside et al. [98].

5. Conclusions and recommendations

This study was conducted to quantify and monetise negative environmental, health and social externalities in Kenya's green bean value chain. The total costs of negative externalities were estimated at 124.03 million USD (range 115.93–132.20) in 2022, comprising 86.87 million USD (range 79.16–94.65) in environmental costs, 0.97 million USD (range 0.58–1.36) in health costs and 36.20 million USD in social costs. The total external costs were at least twice as high as the market value of all green beans in Kenya and almost three times its export value. The environmental costs were the highest due to many ecological externalities. The production stage had the highest external costs compared to domestic packhouses, trade and consumption due to more negative externalities from a range of input-intensive activities carried out on the farm. Adding the environmental costs of air-freighting green beans overseas, the total external costs were three times as high as the market value of all green beans and nearly four times the export value. Similarly, the total external costs were almost twice the average export price of one tonne of green beans and almost equalled its average retail price in Europe. However, increasing the price of fresh green beans with a low environmental, health and social footprint could make the produce unaffordable for budget-constrained, price-conscious consumers.

In conclusion, Kenya's green bean value chain creates substantial hidden costs (negative externalities) for the environment, human health and social welfare of people. Considering all possible gross margins (net income) of value chain stakeholders, the costs of negative externalities in Kenya's green bean value chain are not accounted for in the current average retail price of fresh green beans in Europe.

The implications of the study for stakeholder and policy actions lie in the need to internalise (compensate for, prevent, reduce, restore or stop) negative externalities in Kenya's green bean value chain. There is a need for the Kenyan government's regulatory agencies to routinely monitor value chain stakeholders (farmers, packhouses and traders) and penalise those who generate negative externalities through measures such as fees, fines, license withdrawal and taxes. Strictly enforced and monitored maximum residue limits and water use permits could reduce pesticide misuse and blue water withdrawal. Likewise, packhouse operators' compliance with stringently enforced and routinely monitored limits on air pollutants and GHG-emission reduction technologies, such as carbon capture and storage and vacuum cooling, could reduce human toxicity.

Exporters need to provide fair minimum prices to contracted farmers who adopt externality reduction measures, thereby increasing farmers' income. This requires visiting farms without prior notice to inspect farmers' compliance with agreed-upon standards, including the prohibition of child labour. There is also a need for farmers to join certification schemes, such as Fairtrade and organic farming, to reduce environmental, health and social externalities. Moreover, short message campaigns, social media and meetings targeting farmers, packhouse operators and traders can build awareness of negative externalities and encourage internalisation. Further, there is a need to integrate mandatory carbon accounting into international trade policies, such as the compulsory carbon capture and storage technology in cargo planes and carbon taxes to internalise GHG emissions from air-freighting green beans.

The implications of this study for global knowledge lie in simultaneously quantifying and monetising negative environmental, health and social externalities in Kenya's green bean value chain. This was achieved using true cost accounting approaches, including LCA, DALYs, the True Price methodology and VSLYs. Exposing the true costs of Kenya's green bean value chain can inform benchmarks and targets for reducing negative externalities in this value chain and similar value chains. The benchmarks and targets could be included in environmental, health and social governance metrics, tax schemes and business models. This study provides valuable insights into sustainable value chain governance and decision-making within the context of a circular economy. This research could be a roadmap to facilitate value chain stakeholders and policymakers to meet SDGs, including SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 4 (education), SDG 6 (clean water and sanitation), SDG 10 (reduced inequality), SDG 12 (responsible consumption and production), SDG 13 (climate action) and SDG 15 (biodiversity on land). The study's findings will help decision-makers identify entry points for prioritising interventions and investments that can mitigate the externalities, ensuring that the value chain operates within planetary boundaries and preserves human health and social equity.

Further research is needed to identify internalisation options for the negative externalities in Kenya's green bean value chain and explore stakeholders' willingness to adopt these options to encourage and enforce greater accountability, transparency and responsibility for externalities. In addition, future research may include primary data collection specific to Kenya's green bean value chain to address potential underestimation or overestimation of some negative externalities estimated in the current study.

CRediT authorship contribution statement

Valiant O. Odhiambo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sheryl L. Hendriks:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Odirilwe Selomane:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis.

Ethics approval

The authors obtained ethics approval from the Faculty of Natural and Agricultural Sciences Ethics Review Committee at the University of

Pretoria to conduct the research under reference number NAS117/2023.

Consent for publication

The authors consent to the publication of this paper.

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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 appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2026.102639.

Appendix A

Negative environmental and social externalities and their footprint indicators and monetisation factors.

Externalities	Footprint indicators	Unit	Monetisation factor (INT$) in 2021 per unit of measurement	Monetisation factor (INT$) in 2022 per unit of measurement	Description
Environmental externalities					
Contribution to climate change	Greenhouse gas (GHG) emissions	kg CO_2-eq	0.224	0.2412	Abatement cost as a marginal value for reducing GHG emissions to meet the two-degree climate targets from a meta-analysis
Air pollution	Terrestrial ecotoxicity from 1,4 dichlorobenzene (1,4-DB) emissions	kg 1,4-DB-eq emitted to soil	0.0004	0.00043	A compensation cost as the median value of ecosystem services lost from terrestrial biomes due to air pollution based on a meta-analysis
	Marine ecotoxicity from 1,4-DB emissions	kg 1.4-DB-eq emitted to seawater	0.0026	0.0028	A compensation cost as the median value of ecosystem services lost from open oceans due to air pollution based on a meta-analysis
	Particulate matter (PM) formation	kg $PM_{2.5}$-eq	75.00	80.78	A compensation cost expressing the value of economic welfare lost from particulate matter emissions to air based on a meta-analysis
	Photochemical oxidant formation from non-methane volatile organic compound (NMVOC) emissions	kg NMVOC	1.18	1.27	A compensation cost expressing the value of economic welfare and ecosystem services lost from NMVOC emissions to air based on a meta-analysis
	Photochemical oxidant formation from nitrogen oxides (NO_x) emissions	kg NO_x-eq	4.19	4.51	A compensation cost expressing the value of economic welfare and ecosystem services lost from NO_x emissions to air based on a meta-analysis
	Acidification from sulphur dioxide (SO_2) emissions	kg SO_2-eq	6.70	7.22	A compensation cost expressing the value of economic welfare and ecosystem services lost from SO_2 emissions to air based on a meta-analysis
	Ozone layer depletion from trichlorofluoromethane (CFC11) emissions	kg CFC11-eq	65.40	70.44	A compensation cost expressing the value of economic welfare lost, including damage to crops from particulate matter emissions to the air based on a meta-analysis
	Ammonia emissions (NH_3) from use of manure	kg NH_3-eq	11.60	12.49	Abatement cost as a marginal value for reducing NH_3 emissions from manure to regulatory targets and the costs to prevent such emissions based on a meta-analysis
	Ammonia emissions (NH_3) from other sources	kg NH_3-eq	10.10	10.88	Abatement cost as a marginal value for reducing NH_3 emissions from other sources to regulatory targets and the costs to prevent such emissions based on a meta-analysis
Water pollution	Freshwater eutrophication from phosphorus (P) emissions	kg P-eq to freshwater	290.00	312.33	Abatement cost as a value for reducing nutrient levels to a regulatory target and a compensation cost expressing economic

(continued on next page)

(*continued*)

Externalities	Footprint indicators	Unit	Monetisation factor (INT$) in 2021 per unit of measurement	Monetisation factor (INT$) in 2022 per unit of measurement	Description
					damage and biodiversity lost from a meta-analysis
	Marine eutrophication from nitrogen (N) emissions	kg N-eq to marine water	20.10	21.65	Abatement cost as a value for reducing nutrient levels to a regulatory target and a compensation cost expressing economic damage and biodiversity loss from a meta-analysis
Soil pollution	Freshwater ecotoxicity through toxic emissions to soil	kg 1.4-DB-eq emitted to freshwater	0.0579	0.0624	A compensation cost as the median value of ecosystem services lost from rivers and lakes due to soil pollution based on a meta-analysis
Land occupation by green beans	Land (grassland/savannah) occupation by green beans	mean species abundance (MSA) *ha*yr	3470.00	3737.19	A compensation cost as the median value of forgone ecosystem services compared to original biomes from a meta-analysis
Land transformation	Land (grassland/savannah) transformation	MSA *ha	313.00	337.10	A restoration cost as the average capital investment and maintenance of ecosystem restoration projects in various biomes from a meta-analysis
Scarce blue water use	Scarce blue water use	m^3 scarce water	1.49	1.60	A restoration cost expressing the cost of desalination of water bodies from a meta-analysis
Soil degradation	Soil organic carbon (SOC) loss	kg SOC	0.043	0.0463	A compensation cost expressing the value of soil lost (chemical, biological, ecological and physical properties) due to SOC loss based on a meta-analysis of shadow prices of soil quality
Social externalities					
Child labour	Underage workers below minimum age for light work (5–12 years) involved in non-hazardous economic work	Child full-time equivalent (FTE)	21,600.00	23,263.20	A retribution cost as a penalty for cases of child labour involving children aged 5–12 years performing light work in non-hazardous conditions based on a meta-analysis
	Underage workers aged 13–15 years involved in non-hazardous and non-light economic work		7970.00	8583.69	A retribution cost as a penalty for cases of child labour involving children aged 13–15 years in non-hazardous and non-light work from a meta-analysis
	Workers above minimum age (16–17 years) and below 18 involved in hazardous work	Child full-time equivalent (FTE)	23,000.00	24,771.00	A retribution cost as a penalty for cases of child labour involving children aged 16–17 years performing hazardous economic work based on a meta-analysis
	Underage workers that are not attending school	Number of children that are not attending school	25,300	27,248.10	A combination of compensation, restoration and retribution costs from meta-analyses. The compensation cost expresses the value of future earnings lost when an underage worker is not attending school during youth The retribution cost expresses a penalty for cases of child labour involving children that are not attending school The restoration cost represents the cost of reintegrating working children into full-boarding schools and supporting their education
Insufficient income for farmers	Living income gap	United States dollars (USD)	1.06	1.14	A compensation cost as a value for restituting the direct gap between a household's annual living income benchmark and net income from green beans based on a meta-analysis

Source: Authors' adjustment of monetisation factors based on Galgani et al. [7].

Data availability

Data will be made available upon reasonable request to the corresponding author.

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