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MINI REVIEW

Sustainable intensification of vegetable production using the cereal 'push-pull technology': benefits and one health implications

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Abstract

'One health' (OH) is a cross-sectoral approach that addresses human, plant, animal, and environmental health problems. The initiative stems from recognition of the convoluted linkages among global health risks and the need for coherent multipronged countermeasures. For agriculture, environmental degradation and biodiversity depletion wrought by heavy reliance on inorganic inputs to meet the needs of the ever-growing human population, are a matter of societal concern. Agroecological-based farming strategies have therefore aptly been promoted as an alternative. The push-pull technology (PPT), which was originally developed to combat stemborer pests and later the parasitic weed Striga is one such example. Undoubtedly, the PPT`s ability to maintain soil health and fertility, human and animal nutrition, and food safety together with crop protection against pests remains a progressive approach for buttressing food production among resource-constrained farmers in sub-Saharan Africa (SSA). In a bid to elevate its nutrition-sensitivity status, we recently intensified the cereal PPT by adding vegetables and legumes whilst simultaneously closing yield gaps through judicious usage of land, and environmental and crop protection based on farmer needs. Such context-based interventions, unlock new benefits for farmers and open new frontiers for research in pest and biodiversity management emanating from crop production infused with food safety and environmental stewardship. Whilst OH has largely received attention regarding animal health and zoonotics, we here opine how sustainably managed crop health, in the vegetable intensified PPT, contributes to the same outcomes through human and animal nutrition, food safety that bolsters developmental goals in gender equity and food security. We conclude that the cropping system can even contribute to fight against zoonotic diseases if companion plants that fend off diseases vectors are incorporated.

Keywords Agrobiodiversity · Ecosystem services · Context-based interventions · Crop-livestock systems · Nutrition-sensitive agriculture

Introduction

Insect pests and low soil fertility are major constraints in crop production for smallholder farmers of sub-Saharan Africa (SSA). For many of them, inorganic fertilisers and pesticides are costly and can cause devastating non-target effects that compromise both human health and environmental integrity (Machekano et al. 2019). Environmental degradation due to overgrazing and perpetual land-use change in response to the increasing human population is another challenge. One health (OH) approach to sustainable agricultural and food production is required to mitigate these public and environmental health problems associated with intensive conventional farming. Central to the OH approach is the recognition of the interconnectedness of human, animal, and environmental health problems and the desired unified responses that sustainably balance various health outcomes. Agroecology has long been regarded as an optimal response to conventional agriculture and recent calls advocate for sustainable intensification of such systems to meet various needs including nutrition, pest management, moisture, and biodiversity conservation (Campbell et al. 2014; Caron et al. 2014; Struik et al. 2014; Struik and Kuyper 2017).

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The agroecologically based cereal push-pull technology (PPT) is a companion cropping system where maize or sorghum is intercropped with leguminous plants of the genus *Desmodium* [Fabaceae] whilst surrounded by Napier grass (*Pennisetum purpureum*) or those of the *Brachiaria* sp [all Poaceae] (Midega and Khan 2003). The *Desmodium* intercrops protect cereal crops by repelling (push factor) stemborer pests including the emerging *Spodoptera frugiperda* (fall armyworm), whilst recruiting parasitoids that further parasitise the pests (Khan et al. 1997; Sobhy et al. 2022). The peripheral grasses attract (pull factor) these pests away from the crop for oviposition without allowing full larval development thereby acting as ecological traps. This creates a dramatic net decrease in pest populations in the field and minimal crop damage thereby boosting yields (Midega et al. 2018).

In addition to poor soil fertility, the parasitic weed of the genus *Striga* is very prevalent in cereal production in areas of SSA. The *Striga* weeds compromise crop health by attaching their roots to those of the cereal crops, poaching both nutrients and water meant for crop growth, consequently reducing yield. In severe cases, *Striga* infestations lead to the abandonment of otherwise suitable farming land (Mudereri et al. 2019). Nevertheless, the leguminous *Desmodium* addresses these constraints making it not only a pest management tool but a pivotal component of building soil health. Therein, the novel isoflavanones of *Desmodium* root exudates induce *Striga* seed germination while others inhibit its radicle growth (Tsanuo et al. 2003; Hooper et al. 2015), causing suicidal germination and subsequent depletion of its soil seedbanks overtime (Khan et al. 2008a, b). Other soil health components contributed by Desmodium include biological nitrogen fixation, improved organic matter and phosphorus content, moisture conservation and increased microbial activity (Drinkwater et al. 2021). In addition, both groups of perennial companion plants used in the PPT serve as important fodder for livestock production where they are periodically harvested for on-farm consumption and sale with significant economic benefits (Chepchirchir et al. 2018; Kassie et al. 2018).

Despite the numerous benefits and successes of the PPT, one of the major challenges facing smallholder farmers in SSA is limited land, a finite resource consistently under pressure. Any further land-use change for expansion of crop cultivation will lead to further degradation of landscapes, defeating efforts towards much-needed biodiversity conservation that enable ecosystem services for agricultural productivity and human well-being. Nutritional diversity is also a lagging factor in cereal-dominated food systems of many subsistence farmers in SSA (de Graaf et al. 2011; Noort et al. 2022). Hence sustainable intensification (SI), which theoretically increases agricultural productivity without further degrading the environment and ecosystem services (Rudel 2020), has been widely touted as a viable alternative for subsistence farmers (Campbell et al. 2014; Struik et al. 2014; Droppelmann et al. 2017).

Whilst the PPT represents a form of SI integrating the crop-livestock system followed by the realisation of ecosystem services such as on-farm biodiversity conservation, pest management, livestock fodder ameliorating land degradation due to overgrazing, the omission of high-value nutrient-rich companion plants was perhaps a disincentive for some farmers with ample grazing land or without livestock. For the latter, opportunities for establishing lucrative trade of fodder have been reported in East Africa (Chepchirchir et al. 2018; Kassie et al. 2018). However, this may likely be more profitable where grazing land or fodder is limited. Hence for many farmers, integrating the PPT with high-value crops such as vegetables remains a major incentive for both nutritional diversity and improved incomes. The practice of intercropping cereals with other crops such as beans and pumpkins is not new to subsistence farming in SSA. However, there have been no cases where intercropping was done for harnessing both nutritional diversity, biodiversity conservation, and ecosystem services provision such as pest management and cultivation of fodder. Using past experiences and current evidence, we discuss the prospects of integrating vegetables and legumes within the cereal PPT (Fig. 1) on meeting OH needs. We also highlight the biophysical considerations fostering biodiversity conservation and ecosystem services, with new frontiers for research and socioeconomic aspects that mediate technology adoption.

Push-pull as an effective approach for land sparing and sharing, and biodiversity conservation

Heavy input-reliant agricultural intensification is generally associated with decreased biodiversity. This understanding is contentious where proponents argue that intensification increases productivity per unit area of land resulting in residual land spared to conserve biodiversity-rich spaces (land sparing). Conversely, non-intensive approaches have been associated with extensive land usage to achieve similar levels of productivity thereby leaving fewer spaces for biodiversity conservation (land sharing) (Desquilbet et al. 2017). Whilst presenting a dichotomy, what is clear is that the land sparing-sharing model stems from a common goal to minimise harm to biodiversity in agricultural landscapes and the opportunity costs therein (Phalan et al. 2011; Phalan 2018). Interestingly, such biodiversity and functionality thereof or its connectivity is rarely characterised or quantified, with all understanding currently based on land parcels left for biodiversity conservation. For SI and various agroecological approaches, emphasis is placed on the increased yield on existing farmland whilst fostering practices that maintain biodiversity and environmental integrity to promote

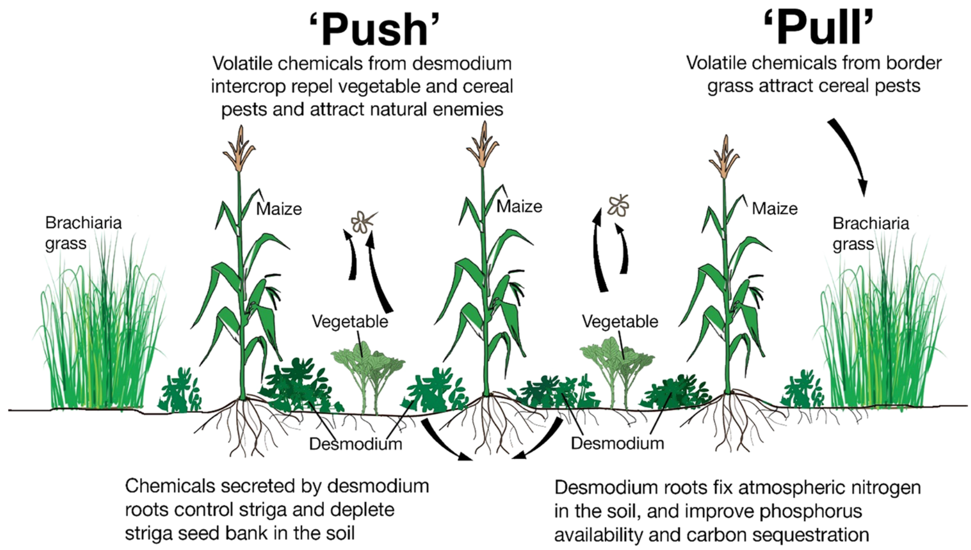

Fig. 1 Schematic diagram of the vegetable integrated push-pull technology (VIPPT) and the pest management and soil health ecosystem services therein

ecosystem services (Tilman et al. 2011; Wezel et al. 2014, 2020). Hence SI, to a larger degree, is very much an extension of the land-sparing approach through higher yields, only without adverse impacts on the environment.

The PPT is a component of the SI paradigm, which interestingly has both provisions for land sparing and sharing. For example, integrating cereals with important fodder crops that suppress pest damage ensures sparing of land as overgrazing is avoided through in situ production of fodder. Indeed, these companion plants are an important component of mixed crop-livestock systems where they have been credited for increased milk productivity (Kassie et al. 2018). Through understanding the intricate chemistry of these companion plants, the cropping system is manipulated such that the increased on-farm biodiversity also recruits various natural enemies that increase predation and parasitism of crop pests (Cook et al. 2007). Thus, to some degree, supporting land-sharing as targeted biodiversity is increased and maintained. Further intensification of the cereal PPT with vegetable integration provides an opportunity for strengthening the provisions for both land-sparing and sharing. Indeed, one of the initial setbacks of the cereal PPT was its failure to account for nutritional diversity and crop rotations. Hence, vegetable integration will not only ensure effective land utilisation and reserve patches for biodiversity conservation but also the realisation of various key ecosystem services.

Functional biodiversity, multitrophic interactions, and harnessing ecosystem services

Enriched biodiversity and the subsequent ecosystem services remain a pivotal component of ensuring high crop productivity and resilience in SI systems. For the cereal PPT, the model meets a set of needs for ecosystem services below and aboveground. Aboveground, the onslaught of a complex of stemborer pests that heavily constrain cereal production in SSA was suppressed through the pest repellent properties of *Desmodium* intercropped companion plants and enhanced pest parasitism through their parasitoid recruitment (Khan et al. 1997; Midega and Khan 2003). Additionally, the peripheral grasses of the PPT lure pests away from the crops due to superior attractive appeal of their volatilome (Birkett et al. 2006). These grasses subsequently act as ecological traps by arresting larval development thereby dramatically reducing crop damage and pesticide usage. Reduced use of pesticides, conserves beneficial insects, including pollinators, thus increasing productivity of pollination-dependent crops.

More recently, this PPT has proved effective against the recent invasive fall armyworm (Midega et al. 2018; Harrison et al. 2019) largely owing to the repellent properties of the *Desmodium* intercrop (Scheidegger et al. 2021; Sobhy et al. 2022). Below the ground, *Desmodium* has been critical in maintaining soil health through suppression of the parasitic weed *Striga* together with fixing the much-needed nitrogen. Additionally, the maize-desmodium intercropping within the PPT leads to the accumulation of soil organic matter and available phosphorous for the crops (Drinkwater et al. 2021; Ndayisaba et al. 2021). Furthermore, plant-soil feedbacks with the PPT have been shown to increase chemical plant defences against pests (Mutyambai et al. 2019). Such ecosystem services have not only boosted crop productivity but also reduced reliance on inorganic inputs, resources that are largely unaffordable for resource-poor farmers of SSA.

The introduction of vegetables within the cereal PPT undoubtedly presents new challenges and opportunities in plot design and manipulation of trophic interactions. For example, most key vegetables for SSA smallholder farmers succumb to a diverse range of pests of various taxa. This, therefore, calls for new lines of research on the chemical ecology and trophic interactions therein. Thus, integrative field and laboratory studies elucidating the trophic interactions within the vegetable integrated PPT (VIPPT) are currently under way. Preliminary results have shown that pest infestation was lower in *Brassica* intercropped with *Desmodium* with subsequent increase in yield attributed to both increased nitrogen availability and reduced damage. This was consistently corroborated by further on-station trials integrating various vegetables within the cereal PPT where pest damage was consistently low leading to improved yield.

Prospects for building resilience under different agroecological regions

On-farm practices can determine the impact of climate shocks (Aryal et al. 2021). For subsistence farmers of SSA, high temperatures and erratic rainfall leading to sustained dry spells are major abiotic constraints for crop production in rainfed systems. Hence, crop and/ or varietal selection forms the first critical step towards local climate adaptation and livelihood resilience at various spatial and temporal scales (Zinyengere et al. 2014). These adaptive benefits can be enhanced by intercropping with resilient crops, a critical component of '*climate-smart agriculture*' enabling in situ efficient resource utilisation and buffering against climate stressors (Nyawade et al. 2019). For example, intercropping improves moisture conservation through the reduction of elevated surface temperature, evapotranspiration, and runoff. The latter does not only improve water infiltration but also supports soil conservation, especially in highland areas where soil erosion can be rampant. Despite all these benefits, attention should be focused on the complementarity to ensure favourable microclimates for the mixed crops and efficient usage of light per unit area for optimal agronomic performance. For example, intercropping improved crop water productivity in rainfed potato following intercropping with legumes owing to soil temperature optimisation and radiation use efficiency (Nyawade et al. 2019).

For the PPT, several climate change mitigating strategies have previously been reported including the development of the 'climate-smart PPT', which employs more drought and heat tolerant companion plants compared to the conventional one (Midega et al. 2018). These seminal innovations were eventually followed by the third generation PPT, which not only tackles climate stressors but also biotic constraints inflicting the companion plants, particularly mites occurring on Brachiaria cv. Mulato (Cheruiyot et al. 2021a, b). These three variants of the PPT provide important options matching different agroecological zones and farmers` needs. More importantly, integrating with locally adapted vegetables and legumes creates even more climate resilient options for farmers under different agroecological zones. Furthermore, the addition of vegetables within the PPT can cushion farmers against climate shocks and total crop failure. This is particularly important in cases where early and late maturing crops are intercropped together such that early maturity enables crops to escape transient adverse abiotic conditions within a season. Moreover, vegetables and legumes offer nutrient-rich diets that are often lacking in cereal-dominated food systems.

From the foregoing, selection of VIPPT crops has therefore been based on farmer preferences where climatic compatibility and prime market value were central to decision making. Hence, farmers in drought-prone areas opted for the more resilient sorghum and millet in place of maize whilst integrating with largely robust indigenous vegetables such as African nightshade (*Solanum scabrum*). In all cases, complementarity among the intercrops is of paramount importance to minimise trade-offs including over-shading, competition, and weediness.

Alignment with the one health initiative

One Health approach recognises the interconnectedness of human, animal, and environmental health and the need for judicious stewardship of all health paradigms to ensure human wellbeing (FAO et al. 2020). In this era of global pandemics (including those of zoonotic origin), climate change, and invasive alien species, all attributed to various deleterious impacts of anthropogenic activities on the environment and/ or biodiversity, environmentally benign farming methods have been brought to the spotlight as countermeasures to mitigate some of these challenges. Although the original OH framework was anthropocentric with much focus on zoonotic pathogens and non-crop plant life (Van Bruggen et al. 2018), recent reports have linked the importance of integrating plant health to the OH concept (Falkenberg et al. 2022; Hoffmann et al. 2022), where pest management and environmental health takes center stage (Ratnadass and Deguine 2021).

For the VIPPT, a crop-livestock farming system designed largely for managing crop pests, several attributes conform to the OH concept (Fig. 2). Owing to its biologically intensive ways of controlling pests, the reduction of farmer reliance on synthetic pesticides is one obvious benefit of the PPT addressing food safety (human health), socioeconomic and environmental concerns for smallholder farmers. The adverse impacts of synthetic pesticides on the environment and human health are well documented (Macharia 2015; Machekano et al. 2019; Diallo et al. 2020). More recently, Ratnadass and Deguine (2021) reviewed the link between pesticide usage and viral zoonotic risks with agroecological pest management strategies as alternative mitigative measures. Pesticide usage against disease vectors in public health has been associated with development of resistance by crop pests facing agriculture pesticides of similar

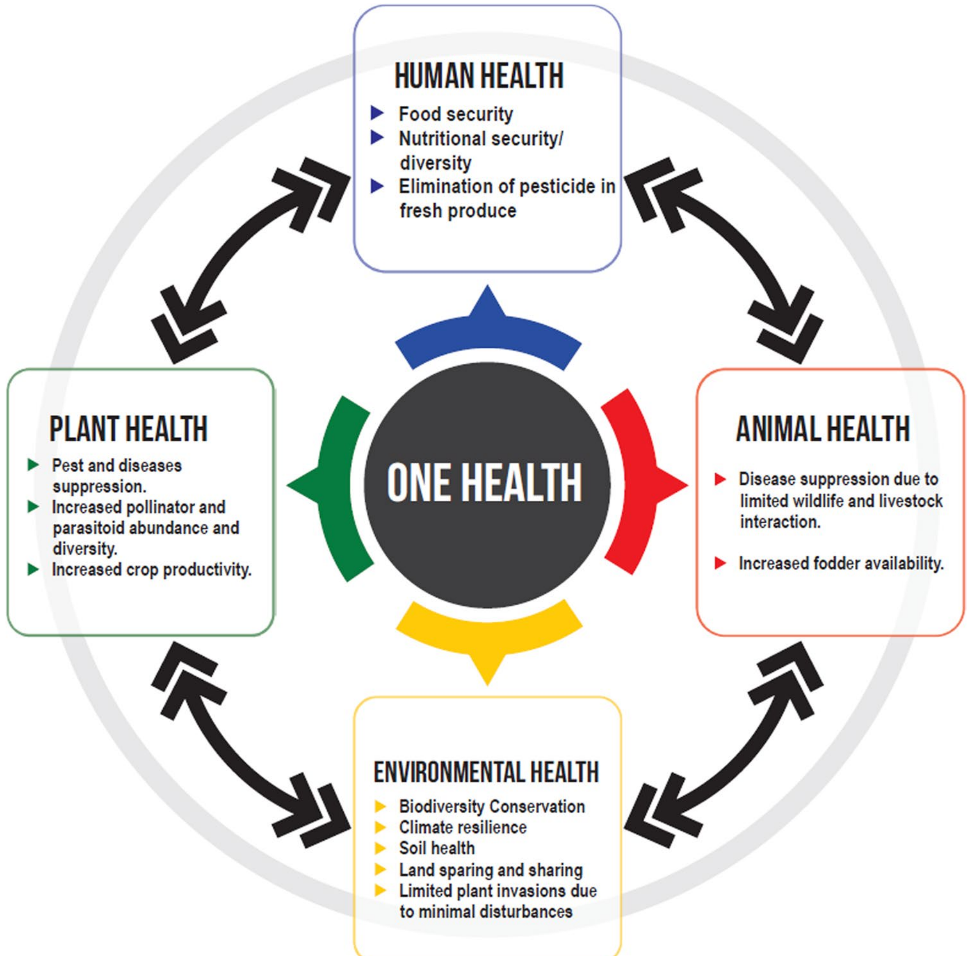

Fig. 2 Provisions of the sustainable vegetable integrated push-pull technology (VIPPT) in alignment with the One Health approach

chemical groups (Venter 2018; Liu 2019; Ratnadass and Deguine 2021). Although in another case pyrethroid application against rice weevil (*Lissorhoptrus oryzophilus*) led to a reduction in mosquito population (Lawler et al. 2007), it is apparent that pesticide usage in agriculture can have direct links with the occurrence of vectors of zoonotic diseases warranting more attention. In addition, high rates of disturbances associated with conventional agriculture often lead to proliferation of invasive alien plants, some with devastating effects on both human and animal health. For example, the neotropical herbaceous invasive alien plant *Parthenium hysterophorus* typically invades degraded farming lands (McConnachie et al. 2011; Chidawanyika et al. 2017; Strathie et al. 2021), leading to a reduction in crop yields including maize (Safdar et al. 2015). The weed is toxic for animals and taints meat and milk products, and also further compromises human health by inducing allergies. In addition, recent reports have linked the parthenium weed with replenishing energy reserves and boosting the survival of malaria vector *Anopheles gambiae* with potential for worsening malaria cases (Nyasembe et al. 2015). Through minimal tillage and reduction of overgrazing through fodder provision, the VIPPT helps in limiting on-farm infestations of parthenium where area-wide adoption may conserve African grasslands and ultimately negating the contribution of parthenium on malaria incidences.

For SSA, vegetable production constitutes one of the major consumers of synthetic pesticides due to significant pest pressure, native or invasive (Ngowi et al. 2007; Macharia 2015; Machekano et al. 2019). Through the integration of vegetables within the PPT, farmer usage of pesticides is further reduced thereby mitigating risks associated with vector populations and toxicity due to direct consumption. Furthermore, vegetable cultivation within PPT may help add much-needed micronutrients to the diets and food systems of SSA. Dubbed the 'hidden hunger', dietary micronutrient deficiencies are indeed a global problem where both poor food choices and unavailability of healthy foods can exacerbate the problem (Ibeanu et al. 2020; Ruel-Bergeron et al. 2015). In addition, the mixed crop-livestock approach of the PPT has already proven invaluable by improving milk (another rich source of micronutrients) productivity through fodder provision. Hence, the VIPPT together with milk provision may help in averting the 'hidden hunger' in diets that are currently dominated by cereals.

Economic incentives and importance in the technology adoption

The adoption rate of agricultural technologies with higher crop productivity is relatively low in SSA (Shikuku and Melesse 2020). Several organizations have however made tremendous efforts in promoting the uptake of improved agricultural technologies. The International Centre for Insect Physiology and Ecology (ICIPE) has used several pathways to disseminate and encourage the adoption of PPT to help improve the production and yields of cereal crops and fodder (Khan et al. 2008a, b). Whilst adoption may be relatively high in Western Kenya, there is still a need for scaling up the technology to various regions.

Like many other technologies, it has become apparently clear that farmers adopt agricultural technology when they derive maximum benefits subject to existing constraints (Khonje et al. 2015). An increase in cereal yields is expected to boost food production where surplus can be sold to generate income (Kassie et al. 2018; Midega et al. 2010; Ndayisaba et al. 2020; Ogot et al. 2018). The economic contribution of conventional PPT is well documented. For instance, evaluating the farm- and market impacts of PPT in western Kenya, Kassie et al. (2018) reported that PPT adoption increased maize yield by 62%. Although the cost of production increased by 15% due to additional labour requirements, this was surpassed by net maize income, which increased by 39%. A recent study by Gugissa et al. (2022) in Ethiopia, similarly found that PPT reduced maize yield loss due to devastating FAW by 10–17%, and generally increased maize yield by 12–15%. The introduction of vegetable into PPT now provide farmers with additional synergy on farmer's income as well as food and nutrition security. Vegetables mature faster and can be grown both during on and off cereal season thus providing continuous income and food for household use and surplus for the market. This further allows for crop rotations, particularly during maize off-seasons. Vegetables are also known to be highly marketable with a higher benefit-cost ratio than cereal crops (Rai et al. 2019). Moreover, vegetable farming does not only employ farm owners but also the surrounding community members through wages for their labour on the farm (Yessoufou et al. 2018). Vegetables further provide employment opportunities to various market value chain actors including youth and women who are over-represented in such fresh produce value chains.

The farmers' choice to adopt agricultural technologies can also be determined by accessibility to inputs. For instance, the PPT has been perceived by farmers to be labour intensive during the initial establishment but the need for such labour diminishes over time once the perennial companion plants are established (Khan et al. 2008b; Murage et al. 2015). Indeed, farmers have reported reduced weeding requirements, land preparation, and irrigation as a result of adopting PPT (Murage et al. 2015; Diiro et al. 2018). The reduced labour demands translate to lower production costs and thus higher profits. Besides, PPT provides high-quality forage reducing the time spent looking for fodder for livestock. The availability of forage through PPT adoption has also led to other co-benefits such as increased livestock ownership, and milk production for both domestic use and surplus for the market, which further improves household income (Muriithi et al. 2018). The VIPPT will therefore enhance the benefits of the technology through increased food and income for the target farming communities.

Vegetable value chain, policy development, and scaling-up opportunities

The sustainably intensified VIPPT involves the integration of both high-value commercial and indigenous vegetables. Vegetables are a nutrient-rich food that contribute to food and nutrition security and thus enhanced health, but also an important source of household income. Particularly for SSA women who are often resource-constrained to invest in capital-intensive enterprises (Deissler et al. 2021). Inadequate information, poor technology dissemination, and limited extension services have resulted in the underdevelopment of the vegetable value chains. In particular, these challenges have resulted in lower adoption of indigenous vegetables and limiting market supply apart from seasonal scarcity. Indeed, consumption and utilization of indigenous vegetables is low during the off-season but increases on-season partly due to low prices as a result of surplus on the market (Laibuni et al. 2018). Given the variability of such produce based on geographic location and climate, value chain development and governance should ensure elaborate distribution networks and quality assurance (Alulu et al. 2020). Social capital and networks incorporated into the intensification of the PPT system will thus be also key to improve indigenous vegetable value chain development, where value chain actors will play a role in knowledge development and sharing (Kassie et al. 2018).

Production and market access for high-value crops among smallholder farmers is often undermined by the complexity of the value chains in the ensuing agribusinesses (Humphrey 2006). Policies aimed at supporting such farmers are therefore not only necessary to promote access to resources and information necessary for increased vegetable productivity and utilization, but also to enhance their income. Extension services currently focus more on agronomic aspects of production but play a (Fadeyi et al. 2022) limited support regarding the trading of produce. Innovative and enhanced extension services should therefore boost both production and marketing to improve the farmers` income. Such extension services can be supported with enabling policy that fosters vibrant national research programs, investigating the production and market dynamics in smallholder value chains (Magogo et al. 2020). As the demand for vegetables continues to grow, partly due to increasing health awareness and the associated lifestyle changes (FAO 2017; Ndyetabula 2022), a strong vegetable value chain linked to the VIPPT will not only contribute towards income, but also support human health through improved nutrition.

Gender disparities and empowerment

The PPT has been dominated by smallholder farmers (particularly women) whose cereal production is hampered by reduced land, limited resources, harsh climatic change, and weak policies (Murage et al. 2015; Ouya et al. 2020). The need of integrating women's empowerment into nutrition-sensitive agricultural programs such as VIPPT is evident (Diiro et al. 2018; Kassie et al. 2020). Earlier studies on conventional PPT reported several benefits including improved dietary diversity score following women`s technology adoption and empowerment.

According to Manda and Mwakubo (2014), gender inequalities on major productive agricultural assets like land are more pronounced in SSA, particularly due to cultural norms. Male farmers often dominate high-value crops while women are in less lucrative value chains. Furthermore, women farmers tend to have limited access to market information, extension services, credit, and technologies compared to men. These gender inequalities are often associated with low agricultural productivity of female-managed farms (Quisumbing and Pandolfelli 2010). Addressing the gender inequality in agricultural systems can therefore, transform livelihoods for rural communities, enhance economic growth and reduce poverty in developing countries (Kristjanson et al. 2014).

Gender equity and women empowerment are inextricably linked, and both play a key role in enhancing the adoption of agricultural technologies in SSA (Alkire et al. 2013; Seymour 2017). The gender nuances regarding technology adoption and its impact may thus also influence VIPPT adoption and subsequent achievement of OH goals. Hence, gender mainstreaming of the VIPPT during dissemination of the technology will be vital. Moreover, women comprise most of the vegetable value-chain actors in SSA. Therefore, targeted involvement of women within the VIPPT and subsequent value-chains will improve technology adoption.

Conclusion

Context-based interventions are key to addressing food and nutritional insecurity of resource-poor farmers in SSA. Through incorporation of farmer needs in nutritional, market, climatic compatibility, and several indirect ones, the VIPPT is a boost for smallholder farmers in this region. Whilst the cropping system helps in crop protection, soil health, food safety, human and animal nutrition, there is room for improvement. At farm level, focus should now also be placed on fodder plants that not only fend off crop pests but also animal disease vectors. This includes tick-proofing, which may be achieved by repellent plants directly even after ingestion where livestock that consume repellent plants are less preferred. These additional benefits may help alleviate the burden of livestock diseases and improve the sustainability of the mixed farming system. Such locally developed solutions, together with farmers, are urgently needed for increased behavioural change and adaptation to address regionally specific problems towards environmental sustainability and OH in African agriculture.

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