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Review article

Ethiopia's wheat production pathways to self-sufficiency through land area expansion, irrigation advance, and yield gap closure

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ABSTRACT

Ethiopia is the second largest wheat producer in Africa. Though wheat production has been increasing steadily in the past decades, the demand for the crop outstripped domestic supply and forced the country to cover about 30 % of the deficit through commercial imports and food aid. The utilization of wheat is rising at 9 % annually while the production is increasing at 7.8 %, showing a continued widening between consumption and production. With a growing demand due to bourgeoning population, increase in income, and preference toward wheat-based products, the country has a long journey to achieve wheat self-sufficiency and save the scarce foreign currency reserve spent on import. The government of Ethiopia is committed to self-sufficiency through initiatives such as wheat area expansion, irrigation development and yield gap closure. In this review, we explored wheat production trends and the roles of the recent government initiatives toward wheat self-sufficiency. The review indicated that wheat production and productivity have increased in Ethiopia, but the wheat self-sufficiency of the country has declined from 99 % in the 1960s to 70 % at present. The future land area expansion in traditionally wheat-producing areas is limited, and wheat land suitability and yield potential is likely to reduce under climate change. Thus, the options to transform the wheat sector while reducing greenhouse gas emissions is through yield gap closure through intensification on existing cropland and judicious temporal and spatial expansion of irrigated wheat areas. The yield gap closure requires higher and more efficient input supply and utilization, investments in modern technologies, as well as supportive agricultural policies. To improve the productivity of small landholder farmers and increase intensity of production through irrigation investment on irrigation structures and facilities is required. Finally, we recommend further studies on yield gap analysis, the role of government initiatives, and wheat land suitability under current and future climate change scenarios at the local level.

1. Introduction

Wheat is among the most important staple food crops and a major diet that is consumed by more than 2.5 billion people globally [1]. It is a staple food in all parts of the world and supplies 35 % of food and provides 20 % of the calories [2]. Wheat is cultivated on an estimated 217 million ha, making it the most widely grown crop in the world, and in terms of production it accounts for 752 M tonnes [3]. The trade for wheat is greater than any other crops combined, where the amount traded globally reached 25 % of the production in

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2018 [4]. Wheat is grown over a wide range of agroecologies ranging from arctic to humid regions, and from below sea-level polders in the Netherlands to 4500 m altitude in Tibet [5,6]. In addition to its adaptability, the ease of grain storage and processing for foods and food products is another advantage of the crop.

The production of wheat over the past 60 years, particularly between the 1960s and 1980s, was dramatic [3]. During this period the cropped area has almost remained relatively constant (204 M ha in 1961 compared to 219 M ha in 2020) and, therefore, most of the production increase (from 222.4 M t in 1960 to 760.9 M t in 2020) has occurred through yield improvement associated with the development of high-yielding cultivars, use of large amount of agrochemicals and better agronomic management practices. The global yield average has increased from 1.09 t/ha in 1961 to 3.45 t/ha in 2020. Global wheat production must continue to increase to feed the burgeoning global population that is expected to reach 9.8 billion by 2050, where 50–60 % more food is required to meet the additional demand [7].

Ethiopia is the second largest producer of wheat in Africa (next to Egypt) and produces 5.5 Mt wheat, which is equivalent to 21.7% of wheat produced and 18.3 % wheat area harvested in Africa [3]. In terms of acreage wheat ranks fourth next to tef (*Eragrostis tef* Zucc.), maize (*Zea mays* L.), and sorghum (*Sorghum bicolor* L. Moench), respectively [8,9]. According to Ethiopian Statistics Services [9] wheat accounts for about 12.2% harvested area (1.9 million ha), 20.2 % total production and employment for 4.9 million subsistence smallholder farmers. Regionally, the largest volume of wheat originates from Oromia (ca. 53 % wheat area and 57–58 % of the national production), Amhara (34 % wheat area and 28–32 % of the production), SNNP (8 % wheat area and 8 % of the production) and Tigray (5 % wheat area and 3–6% of the production) [10,11] (Fig. 1). In terms of consumption, wheat is the second most important food crop next to maize and accounts for 14 % of the total national calorie intake. Wheat is milled into flour for traditional bread, bakeries, pastries, couscous, mixed with other cereals to make *injera*, and also used as *kolo* (roasted whole grain) or *nifro* (boiled grain). Wheat also serves as an important source of income for the small-holders [12]. In addition to the grain the straw is used as animal feed, fuel, source of income and for roof thatching.

Yet wheat production in Ethiopia is dominated by a subsistent smallholding farming system and the productivity is affected by complex and interwoven biophysical and socio-economic challenges [13,14]. For long time the wheat productivity has remained stagnant at very low levels, and food production has lingered behind population growth [12,15,16]. Thus, to fill the widening gap between wheat consumption and wheat production the country has to import substantial quantities of wheat for almost half of the past century both in the form of commercial import and food aid. Currently, the wheat utilization is growing at faster rate than any other food crops due to the rapid population growth, income growth, urbanization, climate change and changing consumption preferences towards wheat-based food items [17,18]. The lack of adequate foreign exchange reserves to pay for food imports is also a concern. With the continued natural and man-made production and trade disruptions, dependence on wheat imports has serious ramifications for one of the countries at greatest risk of food insecurity by 2050 [18,19]. Thus, achieving food self-sufficiency and reducing the spending of scarce foreign currency reserves for wheat import is a national priority [12]. The government of Ethiopia plans to ensure wheat self-sufficiency through land expansion, agro-clustering of wheat farmers and expansion of irrigation spatially to lowlands and temporally to dry season of the year. At issue is to what extent Ethiopia can meet the demand for wheat through the government

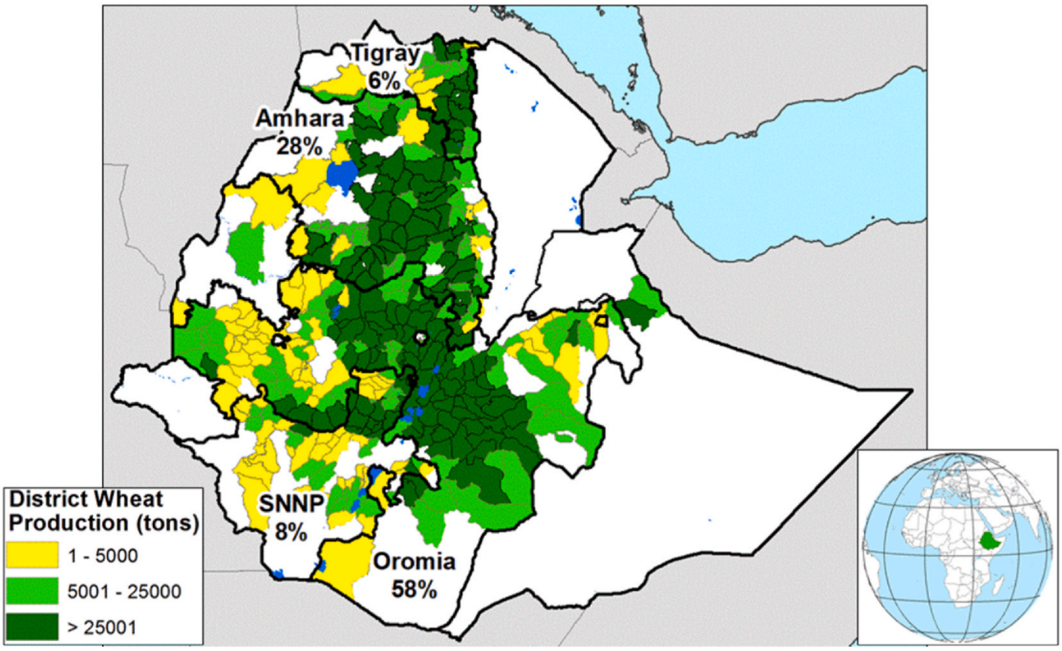

Fig. 1. Average wheat produced in major wheat producing regions and districts of Ethiopia as computed from Ethiopian Statistics Services data-2011-2016 [11].

initiatives under current and future climate change scenarios, and what challenges exist ahead while targeting wheat self-sufficiency horizontally through land area expansion and vertically through yield gap closure?

The aim of this review is, therefore, to explore wheat production trends, and scrutinize the government initiatives for wheat self-sufficiency, and consider the intervention directions to boost wheat production. We focused mainly on wheat crop because of the continued rise in its demand, its lion's share of the food import and the increased government's attention toward the crop. The review focuses on (1) trend of wheat production and utilization in Ethiopia since the 1960s (2) government initiatives of temporal and spatial expansion, irrigation expansion and yield gap closure through agro-clustering (3) analysis of the options and constraints towards food self-sufficiency. The study used information from reports, journal articles, working documents, online documents, government offices and other relevant literatures. The online data searching was done systematically using Google scholar database by employing key terms including: 'land area', 'yield gap', 'irrigation' and 'constraints' along with 'wheat in Ethiopia' in order to get pertinent information that could help address the review questions. The database searching was conducted from June 2022 to December 2022.

2. Wheat production, utilization and import trend in Ethiopia

Both durum wheat (*Triticum durum* L.) (tetraploid) and bread wheat (*Triticum aestivum* L.) (hexaploid) are cultivated in Ethiopia. Durum wheat has been indigenous to Ethiopia and the country is considered as one of the centers for tetraploid wheat [20,21]. Several landraces of durum wheat has been cultivated in Ethiopia and the Ethiopian Biodiversity Institute (EBI) hold a collection of more than 7000 landraces. Durum wheat has been the dominant wheat crop cultivated in Ethiopia for thousands of years, and it is used to prepare several traditional foods such as *injera* (fermented pancake-like flatbread), *kita* (unleavened bread), *kinch*e (boiled coarse-ground wheat), *nifro* (boiled whole grain), *kollo* (roasted whole grain), *dabo-kollo* (ground and seasoned dough) and *atmit* (porridge mixture used as nutritional supplement). However, due to weak progress in the yield improvement and its low genetic diversity exploitation, the land area of durum wheat has dwindled from its peak area of 0.6 Mha in 1960s and 1970s to about 0.27 Mha at present [22]. Yet Ethiopia accounts for the 90 % of 630,000 ha land cultivated with durum wheat in Sub-Saharan Africa [21]. Some researchers consider the Ethiopian durum wheat landraces as an ignored and unexploited for its genetic diversity, which consequently influenced farmers interest in its production [23]. Whereas, the bread wheat is non-Ethiopian and it was introduced in 1940s. In terms of production bread wheat overtook durum wheat since the mid-1980s [15] and now it accounts for 93% of wheat produced in the country.

Regarding wheat production trend in Ethiopia (Fig. 2), the data for the 1960s is scanty and results are mostly estimates due to poor infrastructure and weak statistical capacity, and thus the uncertainty is higher [24]. Yet the wheat self-sufficiency of the country in the 1960s was estimated at 99 % [25]. In the 1970s, following the toppling of feudalistic imperial regime by the Marxist Military regime called *Derg*, the wheat yield has plummeted in terms of cultivated area and production, where the cultivated area of cereals in general has dropped steeply by 31 % [24]. The *Derg* abolished the feudalistic land tenure system and declared all land to be the property of the state, and alternative farming structure such as producer cooperatives (collective farms or *amrach* in Amharic) and state farms were created. The producer cooperatives and state farms were given priority by *Derg* and became focal point for innovations while disregarding the private peasant farmers accounting for 90 % of the agricultural area and production [26]. Moreover, the radical socialist production ideology of marketing and pricing control and restriction of free movement of agricultural products discouraged private farmers. Coupled with the nationalization of production asset, the turbulent political and institutional environment, the involuntary and hurried dislocation of rural communities through villagization program and the recruitment of the young for the military, the disincentives and marginalization of smallholder private farmers beginning in 1975 led to decline in cereal production and lose of incentives for production. This created significant repercussion on the agricultural sector, reduced per capita food availability and increased food aid by ten-fold [24]. The drought that caused repeated crop failure particularly in Wollo and part of Tigray was also blamed as an additional cause for food shortage and famine.

Following the fall of the *Derg* regime in 1991 the *Ethiopian People's Revolutionary Democratic Front (*EPRDF) came to power and identified agriculture as a pillar for sustainable growth determining the growth of all other sectors, and introduced Agriculture

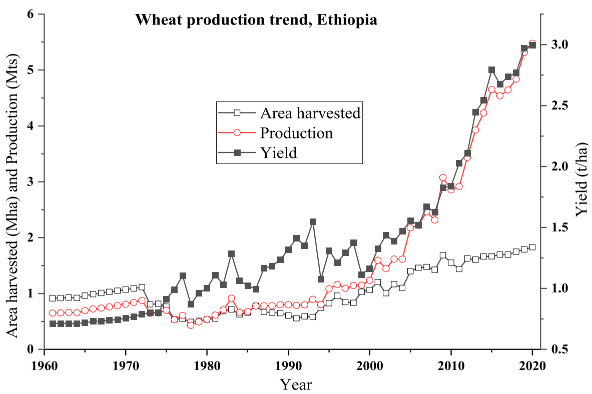

Fig. 2. Wheat area coverage, production and productivity in Ethiopia from 1960 to 2020. Source: FAOSTAT.

Development Led Industrialization (ADLI) policy as a central pillar of national economic strategy to intensify cereal production, accelerate economic growth and ensure food security [27–29]. The EPRDF program was witnessed to be largely successful in liberalization of market for agricultural products, increasing extension services, improving in use of agricultural inputs such as seed and fertilizer packages as seen from more than decades of consistent and sustained economic growth [26,30]. Ethiopia achieved one of the highest Development agent (DA)-to-farmer ratios in the world, and the number of smallholders using extension advisory service tripled from 3.6 million in 2004/05 to 10.9 million in 2013/14, which is 33 % in 2004/05 and 71 % in 2013/14 [29]. By investing in agricultural transformation more food was produced, more employment was created, and hunger and poverty was reduced [30,31].

However, under the EPRDF the import of agricultural commodities such as wheat continued to rise and costed the country millions of dollars every year. The number of safety net beneficiaries has also increased, and only some progressive farmers improved labor and land productivity. Moreover, the EPRDF did not question the former land ownership right and re-affirmed that “the right to ownership of rural land and urban land, as well as of all natural resources is exclusively vested in the state and the peoples of Ethiopia” (Federal Democratic Republic of Ethiopia 1994, Article 40). In fact the farmers are allowed to sub-contract or rent land on a short-term basis and entitled to right to compensation for payments on investments. However, land shall not be subjected to sale or to other means of exchange (Article 40; sub-article 3 of the 1994 Ethiopian constitution).

With regard to wheat, during the initial period of the EPRDF, from 1991 to 2000, the actual yield increase was not significant. However, consistent actual yield improvement was observed since 2000 (Fig. 2). The area under wheat cultivation has almost doubled from 1.02 million hectares in 2000 to 1.9 million hectares in 2020. During the same period the annual production has increased 4.8 fold, from 1.21 in 2000 to 5.78 Mt in 2020, indicating that most of the production increase occurred by intensification rather than land area expansion. In fact the average productivity of wheat has increased from 1.18 t/ha in 2000 to 3.03 t/ha in 2020. The improvement in yield is associated with improved adoption of modern inputs (use of modern dwarf and semi-dwarf varieties, mineral fertilizers and improved access to extension services, improved use of pesticides for pests and disease), large investments in agriculture and improved road and communication networks, education of rural population, and expansion of agricultural extension services [29].

Yet the food production has lingered behind population growth [16,18] and to meet the domestic demand the country has to rely on imported wheat. In fact, the wheat self-sufficiency ratios of Ethiopia has declined from 99 % in 1960s to 70 % in 2022 similar to most other African countries [25,32]. Evidences indicate that Ethiopia annually imported a net average of about 1.6 million tonnes of wheat at a cost of $700 Million US dollar from 2019 to 2022 [33,34]. For instance, in 2016 Ethiopia imported 1.05 million tonnes of wheat of which 750 thousand tonnes takes the form of commercial import and 300 thousand tonnes in the form of food aid [35]. In 2020 Ethiopia imported 61.2 % of wheat from USA, 16.6 % from Argentine, 12.4 % from Ukraine, 4.05 % from Russia, 2.62 from Bulgaria and 2.31 % from Romania [36]. The imported wheat is supplied to flourmills and other processors at a subsidized rate to produce bread for urban population. The commercial grain import is almost exclusively limited to wheat, draining substantial foreign currency from the limited reserve the country has. The 2020 yearly trade indicates that Ethiopia’s export is 3.2 times less than the import, the country earned $3.5B from export whereas expenditure for import was $11.1B, indicating a great mismatch between import and export [37]. In fact, for long time, the lack of adequate foreign exchange reserves to pay for food imports has constrained the commercial purchase of much of the needed grain and to satisfy its demand, thus the country had continually lined among the major food aid recipients for the past half century. At present the consumption of wheat is increasing at a rate of 9.0 % per annum as compared to local production increase of only 7.8 % making the demand to outstrip the supply [38].

The climate change impacts (drought, flooding, heat waves), desert locust infestations in pastoral and semi-pastoral part of the country, internal conflicts that displaced large segments of farming community in the Northern part of the country, has also contributed to the recent rise in wheat import (Fig. 3). Ethiopia was also affected by the COVID-19 pandemic and Ukraine-Russian war that disrupted the value chain of wheat and the price of wheat and wheat products on the global market at large. To ensure food self-sufficiency and reduce the spending of scarce foreign currency reserves on costly wheat import, narrowing the gap between domestic production and utilization has become a core development agenda of the country [12]. Thus, strategic measures including wheat area

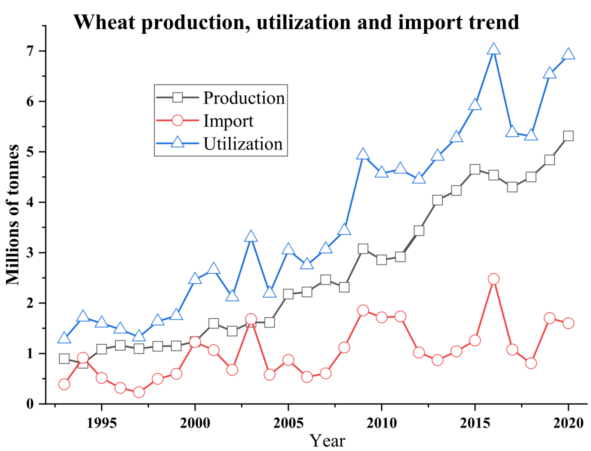

Fig. 3. Wheat production, import and utilization in Ethiopia [3].

expansion, yield gap closure, and irrigation expansion are needed to reduce over reliance on wheat imports and improve food security.

3. Initiative toward wheat self-sufficiency and constraints

To meet the wheat demand and make the country wheat self-sufficient, the government of Ethiopia has devised initiatives such as land area expansion, irrigation advance and yield gap closure by improving productivity through better technology adoption and agro-clustering of smallholder farmers. The government gave serious attention to the wheat sector and the sector is undergoing a significant transformation in production and productivity [12].

3.1. Land area expansion

Ethiopia has a total land area of 112 Mha, of which 30–70 % is believed to be suitable for cultivation and 11–16 Mha is believed to be currently cultivated [39–41]. Most of the land area that can be potentially developed for agriculture are found at peripheries and lowlands, and are not currently suited for production. The harvested area of wheat has increased three-fold between 1961 and 2020 with a rapid increment occurring after 2000 (Fig. 2). In 2021 wheat covers about 2 Mha of land area. In the past two years alone additional 787,000 ha of land was put under wheat cultivation, 187,000 ha in 2021 and 600,000 ha in 2022 [42]. The land expansion in traditionally wheat producing areas is mainly through encroachment of new forest land, conversion of marginal land, re-cultivation using new technologies [18], and by replacing unimproved, input non-responsive traditional cereal crops such as *tef* (*Eragrostis tef*), durum wheat and barley [43]. Hailu et al. [44], for instance, reconstructed the pre-agricultural expansion vegetation and showed that about 75% of current agricultural land in Ethiopia was covered by closed to open shrub land and broadleaved evergreen and deciduous forest during the. The deforestation is, on the other hand, associated with in biodiversity loss, increased rate of soil erosion and alteration of the hydrological balance [45]. To fulfill the rising food demand, the agricultural activity has continued to expand into marginal and high-risk areas of highland and pastoral and agropastoral areas [27]. The continual expansion of wheat land in Ethiopia is in contrary to the global wheat area expansion that peaked at 239.2 Mha around 1981, which latter shrank to the current 219 Mha [3,4].

The wheat output from additional land was expected to reduce the country's wheat deficit but it is not sufficient to fulfill the current 30 % deficit and to meet the annual 9 % demand rise [41]. According to Worldometer online population data of the United Nations, the population of Ethiopia is estimated at 121,451,317 as of Friday, October 14, 2022, ranking 12 in the list of countries by population in the world, and second most populous country in Africa (Ethiopia Population (2022) - Worldometer (worldometers.info)). Ethiopia had a population of 22.2 million in 1960 [44] and 35,240,000 in 1980 [46], indicating a 5.5-fold increase since 1960s and 3.5-fold increase since 1980 respectively. With the current rate of 1.9 % annual increase the population is expected to reach 206 million in 2050. The population pressure alone accounts for three-quarters of the food demand increase [18] and it major driving force for land fragmentation, decreased per capita land holdings, and increased landlessness and environmental deterioration [47]. The land available for expansion is limited in traditionally wheat producing areas, and mainly found at the peripheries of the country, in traditionally neglected regions such as Benshangul Gumuz and lowland dry areas such as Awash and Omo river basins. As observed from leasing of such land to investors, the large-scale commercial and export-oriented agricultural investment results in considerable environmental destruction such as ecological and social trade-offs, biodiversity loss, greenhouse emissions, change in traditional life style and land use rights [41,48]. Thus, expansion of wheat into virgin or under-utilized land presents risks, and wheat area expansion needs to carefully consider the role of these lands in biodiversity conservation, carbon sequestration and other ecosystem services, and crop and nutritional diversification [1,19]. Moreover, the future suitable land area for wheat production is likely to decrease with changing climate, and altitudinal shift of the crop to higher elevations is expected [49].

3.2. Expansion of irrigation

The role of irrigation in increasing production level is clear from the perspective of production ecology, where it removes soil moisture limitation from production levels and raises the yield ceiling to potential yield level [18,50,51]. Many Asian countries such as India and China were able to feed their growing populations and achieved sustained economic growth by investing on massive irrigation infrastructure and by creating enabling institutional and economic environments during the 1960s and 1970s [29,52]. Much of the future food is also expected from irrigated land and yield gap closure in developing countries, and this increase must be achieved under reduced water availability, climate change and evolving pathogen and pest populations [53]. The contribution of irrigation in many African countries such as Egypt, Zambia, Morocco and South Africa is enormous. Similarly, in countries like Ethiopia where smallholder farmers dominate the production and where frequent dry spell and drought results in frequent crop failure and food insecurity, accelerated irrigation investment is needed to reduce the population at risk of hunger and poverty.

> Even though modern irrigation in Ethiopia was started at the Awash River basin in the Rift Valley in 1950s for production of cotton and sugarcane, the development of the sector and its adoption toward other crops is sluggish and showed very little progress [52]. From the existing cultivated area, only 5 percent is believed to be irrigated so far indicating that irrigated agriculture is far from satisfactory despite substantial investment, public interest, and strategic support through government policy. The contribution of irrigation for wheat production is similarly minimal and the vast majority of population is still dependent on rainfed production. For instance, in 2020/2021, only 6190 ha of *meher* and 12,738 ha of *belg* wheat was cultivated using irrigation [10], which accounts for 0.3% of *meher* and 10.0% of *belg* land devoted to wheat.

Ethiopia has a potential to irrigate more than 5 Mha of irrigable land; 4 Mha using rivers, 1 Mha by groundwater and 0.5 Mha by rainwater harvesting [40]. The country has 12 major river basins (Table 1) that provide an estimated annual run-off of about 125 billion m^3. Based on the size of the command area the irrigation development in Ethiopia is classified into small-scale irrigation (<200 ha), medium-scale irrigation (200–3000 ha), large-scale irrigation systems (>3000 ha) (Table 1). About 46 % of the proposed irrigation development is grouped under the small-scale irrigation category [54]. So far only an estimated 4–5% of the potentially irrigable land, ca. 640,000 ha, was utilized with existing equipped irrigation schemes [40]. If fully utilized irrigation can generate around ETB 140 billion (US$ 2.8 billion) per annum to the economy and is able to ensure food security for up to six million households [40].

In very recent years the Ethiopian government devised irrigation expansion as one of the pillars for wheat self-sufficiency and to improve the income of small-scale farmers. Consequently, the irrigated wheat has shown dramatic jump. In 2021/2022 season following government's nationwide wheat planting campaign more than 400,000 ha of wheat area was cultivated by irrigation with the expected production of 1.6 million tonnes [1]. During the 2022 winter season, as of December 7/2022, Ethiopia has covered more than 450,000 ha of land with irrigated wheat [57]. The government policy of agricultural input supply and rural extension services has also been adjusted to meet the requirements of irrigated agriculture, and to support the initiative the government provided free inputs such as seed, fertilizer and pesticides. The wheat produced by irrigation in recent years has played role in cushioning the country from the worst food crisis that could have been caused by value chain constraint of Russian-Ukraine war [58].

However, the recent irrigation campaign was criticized for poor preparation as the program faced challenges including high competition for water, high cost of irrigation pumping, lack of fuel, inadequate irrigation system capacities and limited irrigation water supplies (*personal communication with extension workers*). There was also trade-off between diversion of irrigation water for low value crops such as wheat at the time farmers give priority for vegetable, root crops, and fruit crops for superior income. This can be supported by 153.8 %, 66 % and 16.6 % increment in the irrigated production area of vegetables, root crops, and fruit crops respectively in 2021 compared to 2015 at the time the irrigated area of cereals declined by 8 % during the same period [10,59]. The competition for water resources and trade-offs requires stakeholder participation, and well-informed political decisions. The input subsidization of wheat during dry season irrigation is in fact making the irrigated wheat crop attractive and economically competitive for farmers.

Ethiopia has set a plan to expand irrigated wheat production to a total of 1.5 Mha in the coming 5 years [33]. If implemented efficiently, the country could produce up to 6 Mts of wheat from irrigation alone, which is equivalent to wheat produced in 2021. To couple the government initiatives, research work on irrigated wheat production is in progress by the Ethiopian Institute of Agricultural Research (EIAR). The agriculture research centers such as Worer Research Centers are working on development of stable short duration maturity wheat varieties that are stress tolerant and well adapted to high temperatures. The multi-location adaptation trials using rainfed varieties and introduced wheat germplasms show that wheat grain yield of above 6 t/ha could be obtained in lowland irrigated areas. In countries such as Egypt elite temperature tolerant varieties could yield up to 11 t/ha under optimum irrigation, and thus, the yield achieved in Ethiopia is low and much work is remaining to improve genetic gain under climate scenarios and biotic and abiotic stresses [33].

The main challenge to exploit the irrigation potential of available water is resource limitation to build dams, canals and related structures and facilities for modern irrigation schemes. The lack of capital and technology is the major constraint for irrigation, where the current per capita water storage capacity is 160 m^3 (20% of South Africa's capacity) [40]. Even with reforms such as duty tax free import of irrigation mechanization technologies [60,61], the majority of Ethiopian farmers could not afford acquiring improved irrigation technologies.

In areas where irrigation facilities are present appropriate application, field management and scheduling methods of irrigation are lacking. Eshete et al. [62] reported that irrigation scheduling practices in Ethiopia is very poor and it has been the major challenge for the sustainability of the scheme. The scheduling is supply-based rather than knowledge-based, and scheduling is decided by the local water committee who allocate water for farmers turn by turn or with farmer's intuition without considering the soil, plant, and weather conditions. The majority of irrigation users in Ethiopia are also illiterate and thus over irrigation and under irrigation are common phenomenon [10,62]. Moreover, the currently used furrow irrigation method is laborious and less efficient. Generally, further study is required on challenges of recent wheat irrigation initiatives.

3.3. Yield gap closure

The concept of yield gap was hardly a new term in agronomy, crop production ecology or agricultural economics, but it has re-emerged with the concerns of feeding more than 9 billion people in 2050 [63]. For irrigated systems the yield gap is defined as the difference between the potential yield and the actually observed farm yield [64]. Whereas under rainfed agricultural systems crops suffer at least short-term water deficits, and therefore the yield gap can be defined as the difference between water-limited yield potential and actual yield obtained on farmers field [65,66]. In countries like Ethiopia where the yield gap is very high due to bio-physical and socioeconomic constraints, the yield gap closure has several benefits: it reduces expansion of cultivated areas and concomitant decline in rate of deforestation and biodiversity loss. For instance, by raising yield, the USA farmers have spared 150 Mha from 1940 to 2000 [67]. Yield gap closure is also a strategy to mitigates climate change by reducing potential surge in global greenhouse gas emission [48,68], i.e. emission from intensification is much lower compared to area expansion by clearing forest or pasture land.

The wheat yield gap analysis in Ethiopia has been conducted at national and regional levels (Table 2). According to Global Yield Gap Atlas (GYGA) (www.yieldgap.org) the yield gap of wheat in Ethiopia for the period 1998–2017 is 6.1 t/ha, where the actual yield is only 2.2 t/ha compared to the water limited yield potential (Yw) of 8.3 t/ha. Similarly, Mann and Warner [69] used climate cluster

Table 1
Irrigation potential of Ethiopia by river basins [55,56].

River basins	Catchment area (km^2)	Irrigation potentials (ha)			
		Small scale	Medium scale	Large scale	Total
Abbay	199,890.7	45,856	130,395	639,330	815,581
Awash	112,696	198,632	–	139,627	338,259
Baro-Akobo	75,912				
Denakil/Afar	74,002	2309	45,656	110,811	158,776
Genale-Dawa	171,042	1805	28,415	1,044,500	1,074,720
Mereb Gash	5900				
Omo-Gibe	79,000		10,028	57,900	67,928
Rift Valley	52,739		4000	45,700	49,700
Tekeze	82,350			83,368	83,368
Wabishebele	202,697	10,755.00	55,950	171,200	237,905
Ayisha (Gulf of Aden)	2223	*			
Ogaden	77,121	*			
	1,135,572.7	259,357	274,444	2,292,436	2,826,237.00

*not significant irrigation potential.

methodology in four major wheat producing regions of Ethiopia (Oromiya, Amhara, SNNP and Tigray) and found a yield gap of between 14 and 90 %. The high yield gap in Ethiopia is attributed to the use of outdated technologies that have changed little over the centuries, inadequate infrastructure and institutions, and unpredictable weather patterns. Most smallholder farmers use local or low yielding traditional varieties, limited inorganic fertilizer, sub-optimal tillage practices, sickles for harvesting and animals for threshing. The use of pesticides is limited and the stress from biotic and biotic agents is high. Thus, the small-scale farmers lives are imprisoned within a "cycle of equilibrium" of low margins with low investment, low productivity and low value addition [70].

Globally, Ethiopia ranks 24th in area harvested, 25th in production but 60th in terms of yield [3]. The 3.0 t/ha yield in Ethiopia is lower even with many African countries standards such as Zambia (7.37 tonnes/ha), Egypt (6.57), Namibia (6 tonnes/ha) and South Africa (4.14 tonnes/ha) [3]. If causes of yield gap are identified and investments are made on yield gap closure, the existing yield gap is an opportunity for future food self-sufficiency. For instance, raising the actual average national yield of 3.0 t/ha in 2020 to 4.0 t/ha (50% of water limited yield potential of GYGA) could add 2 Mts of wheat to the national production. This is higher than 1.6 Mts of wheat that is imported annually, and suggests that achieving 50 % of the yield potential can lift the country to wheat self-sufficiency [18]. Thus, investment on yield gap closure through higher and more efficient input use (fertilizers, pesticides, and water) and improvements in crop management could help to achieve wheat self-sufficiency while mitigating global climate change.

The recent wheat yield increase in Ethiopia could not have been possible without the use of improved wheat varieties, acceptance of fertilizer, and improved extension services and agronomic practices. Since the late 1960s regional and national wheat programs in partnership with ICARDA and CIMMYT successfully released over 100 bread wheat varieties. The yields have shown steadily linear improvement over time, where older varieties such as Lakech, Esrael and Enkoy have low productivity compared to lately released modern varieties such as Danda'a, Wane, Hidase, Abay, Dursa, Boru and Daka [33,76]. Many of the older wheat varieties became obsolete due to emerging rust races, low productivity, slow early generation seed multiplication, and weak extension systems in scaling-up of the newly released wheat varieties [19]. The adoption of improved varieties by farmers has also shown improvement [15,

Table 2
Wheat yield gaps from various studies in Ethiopia and major wheat producing regions of Ethiopia.

Author	Location	Actual yield (t/ha)	Yg* (%)
Global Yield Gap Atlas	Country level	2.2	73.5
Silva et al. [65]	Country level	1.9	80
Mann and Warner [69]	Country level	1.7	14–90
	Amhara		51
	Oromiya	1.76	48
	SNNP	1.72	50
	Tigray	1.7	40
Morley et al. [71]	Amhara	1.34	84
	Oromiya	1.81	76.30
	SNNP	1.29	84.40
	Tigray	1.46	73.30
Getnet et al. [72]	Average	1.88	50.7
	Eastern highlands of the RV	2.04	43.6
	Central lowlands of the RV	1.89	77
	Western highlands of the RV	1.72	43.1
Araya et al. [73]	21 wheat producing locations	1.6–3.36	Nd**
Yang et al. [74]	Ethiopia	0.98	Nd
Ayele and Tarekegn [75]	Hadiya of SNNP	1.9	4 t/ha

**Yg* (yield gap) is the difference between water limited potential yield and actual farmers yield).
***Nd* - no data.

29].

The fertilizer adoption has also improved likewise [29]. In the 1990 Ethiopian farmers were reluctant in applying chemical fertilizer for crops such as wheat because of lack of money, untimely and limited availability of fertilizer and fears of burning effects [77]. Uninsured risks such as drought, lack of liquid assets to pay for input, and lack of access to credit also contributed for poor adoption of fertilizer [78]. However, the improved awareness on fertilizer use and adoption since 2000 and consequent rise in its use has led to improved wheat output per cropland (Fig. 4). Yet Ethiopian farmers lagged far behind other developing countries in fertilizer use and the amount used is among the lowest in Africa [79]. The average fertilizer use in Ethiopia is roughly less than 40 kg per hectare, which is much lower than 54 kg/ha in Latin America, 80 kg/ha in South Asia, and 87 kg/ha in Southeast Asia [80]. The study conducted by Tadesse [78] in the Southern highland showed that despite the increasing trends in fertilizer adoption since mid-2003, only 22% of the plots in their study area has actually received fertilizer.

The government of Ethiopia is promoting agro-clustering[1] [81] as a pathway to reduce yield gap and consequently reduce poverty and stimulate economic growth (Agricultural Transformation Agency - ATA). Agro-clustering involves combining tiny smallholdings located in wheat producing agro-ecological zones into crop-specific clusters (larger farmlands) to ease mechanization and access to long-term capital investment. In particular agro-clustering aims to ease access to inputs, credit, information, extension support and mechanization services such as development of irrigation schemes, renting tractors to prepare land and combiners to harvest. The agro-clustering also helps small-scale farmers to get improved market access with higher prices and higher value-added production. The number of smallholder farmers engaged in cluster in four major wheat producing regions was 515,661 in 2019/20 (Table 3), and the plan is to increase the number of farmers joining clusters to nearly 5 million and double their income in five years. The recent figures show much higher as the government claims more numbers.

Evidences show that agro-clustering in Ethiopia improved productivity, household income, reduced poverty, and improved welfare gains for households [83]. However, there are critics toward agro-clustering and its long term effects in Ethiopia. Diriba [27] argued that agro-clustering provides short term breath but does not result in significant increase in income and cannot resolve the underlying causes to poverty. He further stipulated that at the present productivity levels, it is only those households with more than 2 ha of land who can achieve basic subsistence under normal conditions [47]. In fact most significant agro-clustering gains were achieved by wealthier or progressive farmers who owe large land size [83]. The landholding of the majority (or over 90 %)of the farmers in Ethiopia is 1 ha or less, which is often unable to fulfill household consumption leaving alone the saving and creation of wealth by generating market surplus [27,79]. According to 2020 Central Statistics Agency data, from the 5.78 million tonnes of total wheat produced 56 % was used for household consumption, 16% for seed, 24.4% for sale and the remaining 3.6 % is used for wage in kind. Thus, the agricultural intensification brought by agro-clustering is unlikely to achieve the majority of farmers' transition toward commercial companies through market development for sale of products.

The other constraint of yield gap closure through agro-clustering is the shortage of inputs in quality and quantity [29]. The agricultural production clusters are required to adopt the latest full-package farm recommendations, including use of inputs (improved seeds, inorganic fertilizer and pesticides) and other farming best-practices. However, the timely provision and availability of certified seeds, fertilizers, agronomic practice training (row planting, lower seed rating) is lacking or low. The timely delivery and provision of the needed quantity of seed and fertilizers during peak planting times is a big hurdle and complaint from farmers. The formal seed sector has limited capacity to provide the large quantities of seed required for planting, and thus, further efficiency improvement of national seed system is needed to meet the farmers varietal choices [84]. So far the improved wheat varieties usage account for only 13 % of the seed and 19 % of cultivated land, and 19 % of smallholders [85], and about 80 % of the seed delivery to smallholder farmers in the country is dominated by the informal wheat seed system [12,79,84].

The recent price surge of chemical fertilizer and its shortage caused by the Russia-Ukraine severely affected the use of input packages, and many farmers in Ethiopia are obliged to replace chemical fertilizer with organic fertilizer. An extension worker in Gurage zone of Ethiopia was heard saying ''*following the increased fertilizer price in 2022 farmers were unhappy over price increase and they don't even want to see extension workers for advice as if extension workers are the one responsible for fertilizer price hike*''. In fact the increased agricultural input cost is a principal causes of current global food insecurity that increases food prices, and reduces land use intensification, and would consequently lead to agricultural land expansion and associated carbon and biodiversity loss [86].

3.3.1. Decomposition of constraints of yield gap

Understanding the constraints of yield gap are crucial to prioritize policies and interventions towards wheat self-sufficiency under future scenarios [65]. The constraints of yield gap were discussed by different authors in Ethiopia [64,65,87–89]. Many of the studies decomposed the constraints into efficiency, resource and technology yield gap.

The technical efficiency yield gap results from crop management imperfections (inefficiencies) in production such as poor knowledge, skill or information of planting density, planting/application time, poor fertilizer and chemicals application. To close technical efficiency yield gap the extension services and investment in farmer education are the main policy instruments. For instance, most farmers consider row planting as more laborious and costly (particularly at sowing and weeding) compared to broadcasting and or row planting on rows produced by oxen-driven wooden plow (an inter-row distance of about 30 cm) (Fig. 5). Both of the later methods, broadcasting and oxen-driven rows reduces land use efficiency compared to a 20 cm inter-row recommendation for wheat sowing. Moreover, the broadcasting method disperses seeds and fertilizer in a non-uniform fashion, and results in technical

[1] Agroclustreing is concentration of agricultural activities creating income and employment opportunities in and around a particular region.

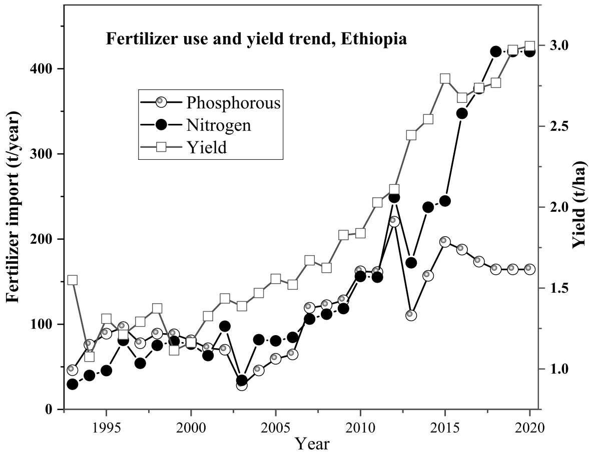

Fig. 4. Trend of fertilizers type and amount used, and wheat yield from 1993 to 2020 (Source: FAOSTAT, 2022).

Table 3
Number of wheat clusters and farmer production cluster (FPC), and land area in major wheat producing regions in Ethiopia.

Region	Number of clusters	Number of FPC Farmers	Land area (ha)
Tigray	2509	101,444	26,699
Amhara	1972	132,922	50,821
Oromiya	5923	190,044	89,072
SNNP	1216	91,251	37,936

Source: Agricultural Transformation Agency (ATA) [82].

inefficiencies of the farming system. Thus, investing alternative sowing technology for row cropping reduces technically inefficient yield gap.

Resource yield gap is the difference between highest farmers' yield and technically efficient yield. The highest farmers' yield is an average yield across top 10th percentile of actual yields in a sample of farmers sharing similar biophysical conditions and adopting similar technologies. Resource yield gap is caused by sub-optimal application of inputs, and can be further decomposed into allocative and economic yield gap [89]. Investment in road infrastructure, provision of credit to overcome financial obstacles, insurance, supporting national for input use and reforms to reduce transactions cost of production have the potential to narrow the resource yield gap [65]. According to Morley et al. [71] resource yield gap contributes for 32.6 % of wheat yield gap in Ethiopia.

Technology yield gap is the difference between water-limited yield and highest farmers' or feasible yield [89]. The lack of access to and availability of appropriate and improved technologies for smallholders in sub-Saharan Africa is one of the major causes for technology yield gap, and it will continue to play vital role under future climate change scenarios [90]. The technologies needed include development of new improved varieties, use of advanced technologies and site specific fertilizer application, which consequently shift the frontier response curve upwards in the direction of the theoretical yield response curve. Silva et al. [65] found that the technology yield gap contributes for more than 50 % of water limited yield of wheat in Ethiopia. Morley et al. [71] suggested that technology yield gap contributes for 57 % of the wheat yield gap in Ethiopia.

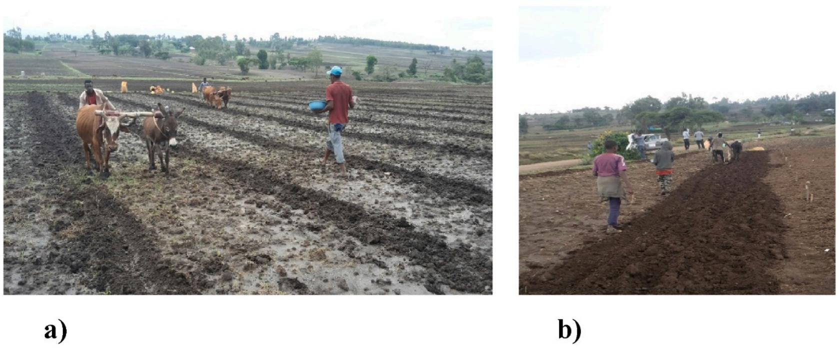

Fig. 5. Wheat sowing in clustered farm areas in Gurage zone, Wudget and Gefersa kebele: a) typical broadcast sowing, b) row planting of seed and fertilizer following the footstep of oxen driven plow.

There are several other studies on yield gap but most of the studies have focused on technical efficiencies using a single attribute of technology: improved variety, input application or other agronomic practices [91,92]. Ayele and Tarekegn [75] for instance compared the technical efficiency of wheat production in row planting and broadcasting methods in Duna district of Hadiya zone of SNNP region, but did not include the resource and technology yield gap. Similarly the national and regional level studies are coarse for biophysically and socio-economically heterogeneous conditions of Ethiopia (soil variability, weather conditions, and farmers' management decisions) and more reliable and rigorous studies are recommended at lower levels.

3.3.2. Climate change impact as a constraint on wheat initiatives

Being a C3 crop, the projected climate changes, particularly rising temperatures, could pose a critical threat to global wheat production [93]. The low latitude tropical regions such as Ethiopia are believed to suffer the greatest losses in terms of productivity and land suitability [94,95]. In Ethiopia most wheat is grown at altitudes between 1500 and 3000 m above sea level [96]. Altitude dictates the distribution of wheat production through its influence on temperature, rainfall, diseases and pests [97]. The most suitable potential wheat areas have minimum temperature between 6 °C and 11 °C and rainfall of at least 350 mm [96] during its growth period. Yang et al. [74] conducted extensive study in Tana Basin, Western Ethiopia, and came up with a conclusion that climate change in the past four decades may have contributed to a decrease in yield and land suitability of wheat. The wheat yield decline was directly correlated with the negative effect of increased minimum temperature on floral induction.

The high temperatures during critical developmental stages of the crop is also risky for wheat-growing areas in the country. Though, agronomic practices such as adjusting planting dates and CO_2 fertilization reduces the extent of effect and ideotyping elite wheat varieties with high yield potential in hot environments are needed to adjust for projected temperature rises of approximately 2 °C by 2050 [98]. The focus of conventional breeding is mostly on improving the yield of crops rather than their tolerance to climate change [99]. The 'selection for yield' and 'defect elimination' also heavily reliant on the availability of a wide range of parents, and requires multi-location and multiyear field experimentations. Therefore, with the changing climate designing of wheat cultivars with high yield potential that can also withstand extreme climate events such as increasing annual temperatures and drought is becoming increasingly important [74,100].

Climate change also induces yield reduction by lowering length of growing season [73,101]. Araya et al. [73] conducted a climate change impact study on productivity of wheat in 21 major wheat producing areas in Ethiopia for mid-century temperature and baseline CO_2 scenario, and found that the yield of wheat decreases by up to 40 % depending on location. However, the loss will be compensated by elevated CO_2 and improved nitrogen fertilizer application. Araya et al. [102] also indicated that temperature rise by 1, 2, 3, 4, 5, and 6 °C for Kulumsa area in central highlands of Ethiopia could decrease wheat yield by 5.1, 10.1, 19, 28.5, 36.7, and 41.5 %, respectively, when compared to the baseline temperature of 1980–2009. They also suggested that improved management practices (optimal nitrogen rate, planting date, and planting density) alone cannot offset the effect of heat stress on yield reduction for temperature above 4 °C. In another study in Tigray region, Northern Ethiopia, Araya et al. [103] has shown that when wheat crop is exposed to temperatures of up to 5 °C above the baseline the yield decrease is greater, which is likely attributed to reduced plant growth length. Similar studies are needed in other parts of Ethiopia to ascertain the impacts of climate change on wheat land suitability and production under current and future climate scenarios.

4. Conclusions and future directions

In order to meet the escalating demand of wheat due to the rising population, dietary changes and income growth over the next several decades' substantial increment in production is required. Significant enhancements have been scored in terms of input acquisition and use, area expansion and productivity of wheat over the past two decades. The current government initiative to address the wheat gap through area expansion, yield gap closure and development of irrigation could contribute towards boosting wheat production and closing the gap between supply and demand. Provided that proper strategies and interventions are identified and executed the country's land, climate and water resources can be suited to increase wheat production and meet the initiatives objectives towards self-sufficiency. Closing the huge yield gap between actual and attainable yields may need to be given priority in order to achieve the objectives sustainably in view of the threat of climate change and environmental protection. On the other hand, timely provisions of inputs with adequate quality and quantity and at affordable prices such as improved seeds and fertilizer is still a hurdle that needs to be addressed adequately. The other way that requires attention for yield gap closure would be to encourage private investment, which can bring in more resources and technology and provide ample employment opportunities. Agriculture by its nature requires a long term investment and the government needs to formulate policies and provide security to attract entrepreneurs that could be engaged in either wheat production and/or improved seed production with relevant checks and balances against cutting corners. Moreover, the 'campaign' nature of the initiative may have its pitfalls in that it may show positive rewards as long as it lasts but success could be short lived once attention is diverted elsewhere. Thus, it would be more sustainable to mainstream the initiative and work on a planned and progressive manner building step by step and through learning from past mistakes. Institutes engaged in research need to come-up with appropriate technologies and agronomic management packages suited to different modes of production and diverse agro-ecologies. Moreover, the pace for mechanization should be increased be it for rainfed or irrigated agriculture if the country has to make substantial improvement in production of wheat and other staple crops. Finally, this study is based on review of existing literatures, and a more detailed ground based studies on prospects and challenges of the initiatives need to be addressed at local levels. The extent of climate change impact on the initiatives and alternative adaptation strategies also needs further investigation.

Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Abate Feyissa Senbeta: Conceptualization, Writing – original draft, Writing – review & editing. **Walelign Worku:** Conceptualization, Supervision, Writing – review & editing.

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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