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Review

Wheat Production and Breeding in Ethiopia: Retrospect and Prospects

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ABSTRACT

Wheat, cultivated on a total area of 2.1 million hectares annually with a total production of 6.7 million tons, is one of the most important food security crops in Ethiopia. However, there is a huge gap between wheat production and supply due to the increasing demand associated with the surge in urban population, change in food preferences such as bread, biscuits, pasta, noodles, and porridge which are easy and quick to prepare. To offset this gap, Ethiopia imports on average 1.2 million tons of wheat annually using its available meagre resources. Though there is enormous potential to increase Ethiopia's wheat production both vertically and horizontally, it is still limited due to key challenges such as prevalence of biotic (yellow rust, stem rust, septoria, fusarium) and abiotic (acidity, heat, drought) stresses, yield gaps due to low adoption of new technologies, high cost and limited availability of inputs, low public and private investments, and poor infrastructure and marketing systems. Wheat breeding in Ethiopia is dominantly carried out by the Ethiopian Institute of Agricultural Research (EIAR) since 1960's and recently with regional agricultural research institutes and universities in partnership mainly with the international agricultural research centers (CIMMYT and ICARDA) to develop high yielding, heat/drought tolerant and disease resistant wheat varieties with broad adaptation and acceptable end use qualities. To date, a total of 88 bread wheat varieties of CIMMYT and ICARDA origin have been released with continuous progress in yield (40 kg ha^{-1} $year^{-1}$) ranging from 2 t/ha of variety Lakech in 1970 to 6.5 t/ha of the new variety 'Abay' released in 2021. This paper summarizes the status of wheat production under rainfed and irrigated environments, production constraints, wheat breeding progress, variety deployment efforts and future prospects in Ethiopia.

KEYWORDS: breeding; challenges; Ethiopia; production; wheat

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STATUS OF WHEAT PRODUCTION AND CONSUMPTION IN ETHIOPIA

Wheat (*Triticum aestivum*, 2n = 6x = 42, AABBDD) is one of the most important food security crops in Ethiopia. It is cultivated on a total area of 2.1 million (1.7 million ha rain fed and 0.4 million ha irrigated) hectares annually with a total production of 6.7 million tons of grain at an average productivity of 3.0 and 4.0 t/ha under rain-fed and irrigated conditions, respectively during 2021/22 [1]. The rainfed wheat production is dominantly carried out during the main rainy season in Ethiopia (June to October) in highlands of the country while irrigated wheat production is carried out from November–April in the lowlands of Ethiopia along the Awash, Wabe Shebele and Omo river basins (Figure 1).

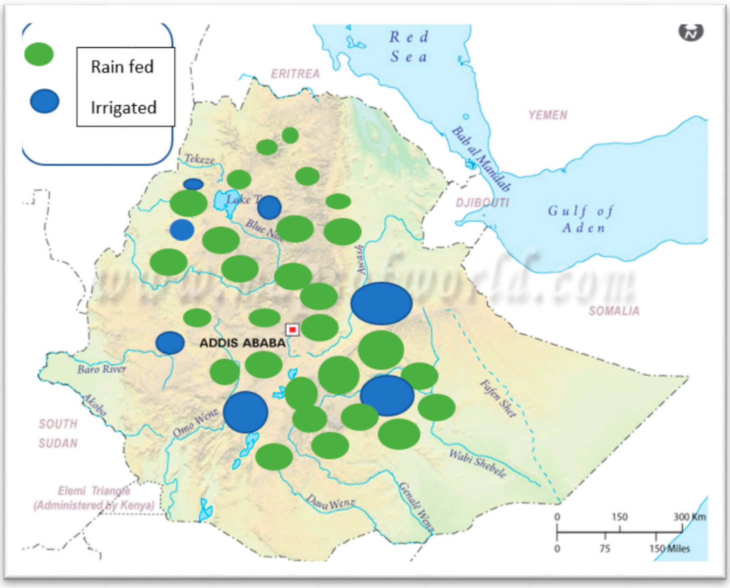

Figure 1. Map of Ethiopia showing the potential rainfed and irrigated wheat production areas and the main river basins.

Both bread and durum wheat are cultivated in Ethiopia. The tetraploid wheat (durum and emmer wheat, *Triticum turgidum*, 2n = 4x = 28, AABB) have been dominantly cultivated in Ethiopia for thousands of years and there have been diverse collections of landraces stored in the Ethiopian national gene bank and other gene banks (Gatersleben, Germany, CIMMYT, ICARDA, USAID etc.). Bread wheat (*Triticum aestivum*, 2n = 6x = 42, AABBDD), which accounts 95% of the global wheat production area, was introduced to Ethiopia in the early 1940's and since 1970's, it is the dominant wheat type covering currently more than 90% of the total wheat production area in Ethiopia [2,3]. As indicated in the production and consumption trend analysis below (Figure 1), the demand for wheat in Ethiopia has been increasing over the years because of rapid population growth and urbanization which necessitated change in food preferences which are easy and fast to prepare such as bread, biscuits, pasta, noodles and porridge from the wheat flour.

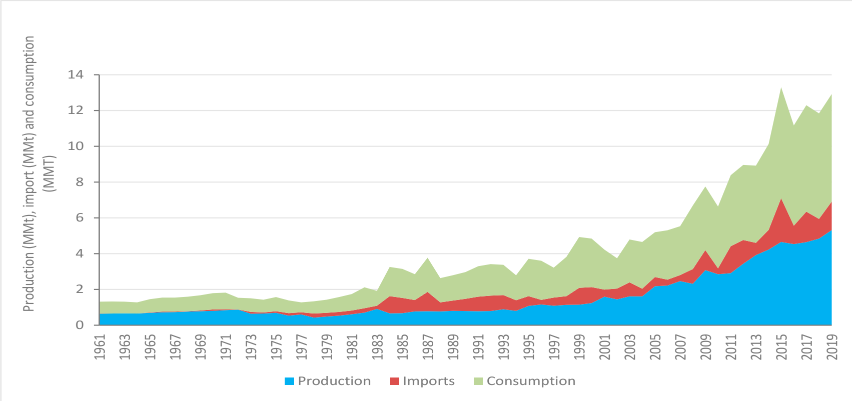

Figure 2. Wheat production, consumption and imports in Ethiopia from 1960–2020 [4].

From 1961–1978, Ethiopia's wheat import was very low, less than 0.2 million tons. However, wheat import increased through years and in the last five years, Ethiopia imported on average 1.5 million tons of wheat at an average cost of 700 million dollars annually (Figure 2). In the last five years, Ethiopia imported on average 1.5 million tons of wheat at an average cost of 700 million dollars annually. The current crisis between Russia and Ukraine coupled with climate change and population increase exacerbated the problem associated with the global wheat demand-supply chain resulting to a dramatic increase in price and limited availability at the global market even for those countries who can afford to buy at any cost. This has forced countries to expand local wheat production as much as possible and look for alternatives including changing food habits.

Understanding and prioritizing the main production constraints are important before embarking on the expansion of local wheat production. Wheat production in Ethiopia suffers from diseases (rusts, septoria, fusarium, etc.), soil acidity, declining soil fertility, terminal moisture stress, heat, mono-cropping, pre-harvest sprouting, and climate change. Furthermore, growing populations, increased rural-urban migration, low public and private investments, weak extension systems, inappropriate agricultural policies, and yield gaps because of low adoption of new technologies remains to be major challenges [4–6]. To offset these challenges and achieve wheat self-sufficiency and export in Ethiopia, it is important to follow a two-pronged approach: (i) Bridging the yield gap in traditional rainfed highland wheat growing areas through developing and scaling climate resilient high yielding varieties and associated integrated crop management practices; and (ii) Expanding wheat production in new frontiers of irrigated lowland areas through developing and scaling of high yielding, heat tolerant and rust resistant varieties with integrated crop management packages. To this end, the government of Ethiopia along with different stakeholders and partners has started to expand wheat production in the lowlands of Ethiopia extensively using irrigation to substitute wheat import, achieve wheat self-sufficiency and create jobs along the wheat value chain. During the 2021/22 season, more than 400,000 hectares of land have been covered by irrigated wheat production.

According to government reports, wheat import could be significantly reduced by 2023 and Ethiopia eyes for wheat self-sufficiency and export by 2025. Involvement of different stakeholders including farmer unions, youth groups, commercial farmers, seed growers, millers, banks, cooperatives, and deployment of favourable policies to enable the availability and accessibility of inputs, extension services, transportation, mechanization and marketing infrastructures are key for achieving the wheat revolution in Ethiopia.

MAJOR WHEAT PRODUCTION SYSTEMS

Wheat is one of the most widely adapted crops grown at different altitude ranges [7]. Though there are high degrees of environmental variations within and between regions, based on moisture availability, cropping systems and temperature regimes, the wheat production in Ethiopia can be divided into two major production systems: (i) Rainfed and (ii) Irrigated production systems.

Rain Fed Production System

The rainfed production system exists dominantly during the summer-autumn seasons in the highlands and mid altitude areas of Ethiopia across the different regions and it was the only system of wheat production up until recently. The wheat cultivation system in Ethiopia is a combination of traditional and modern practices. Most of the smallholder farmers use oxen for ploughing, inputs (quality seed, inorganic fertilizers, herbicides, fungicides), labor for weeding, sickles for harvesting and animals for threshing followed by winnowing using local tools and labors [6]. The harvested grain is stored for local consumption and the straw is used for animal feed. Surpluses are marketed through nearby outlets. However, the productivity of such system is usually low and depends primarily on the availability of rainfall. Mechanized wheat production is implemented through cluster farming which is a mechanism whereby farmers willingly cluster their farms and adopt the same technological inputs including use of machineries such as tractors, planters and combine harvesters. The approach of cluster farming is increasing in many parts of Ethiopia and has contributed for better adoption of mechanization and inputs (seeds, fertilizers, chemicals etc.) and improving productivity.

Different crop rotations such as legume-wheat, potato-wheat, or oil crops -wheat have been widely practiced in the rainfed production system for the various known advantages including improving soil fertility by fixing atmospheric nitrogen, enhancing water use efficiency (WUE), diversification, and breaking the cycle of weeds, insect pests and diseases [6,8,9]. However, wheat after wheat production (mono-cropping) becomes widely implemented in those areas where mechanization has been widely adopted. Farmers in those areas do not want to grow legumes or oil crops in the rotation since there are no combine harvesters specific to these crops in addition to their low yield levels.

Irrigated Wheat Production

Ethiopia is one of the countries in Africa with huge potential for irrigated wheat production. Though traditional small-scale irrigation has been implemented for thousands of years, the Ethiopian agriculture has been fully dependent on rains until recently [10,11]. Ethiopia has a potential of 5.3 million hectares of land suitable for irrigated agriculture using surface, ground and rainwater sources. However, only less than 2% of this potential has been utilized to-date [12]. Medium and large-scale irrigation schemes installation started in the 1950's and continued during 1970's especially along the Awash River basin [13] and expanded recently along the Omo, Genale, Tekeze, Tana Beles, Wabi-Shebele in Somali region and other river basins for the production of sugar cane, cotton and fruits and commercial crops. Research for irrigated wheat production was started as early as 1980s at Worer Agricultural Research Center by the Ethiopian Institute of Agricultural Research (EIAR). However, there was no irrigated wheat production in the region even though there have been irrigation schemes developed for cotton production. Surprisingly, there has been no thought by the cotton farmers for using such land for double cropping with wheat or other legumes after harvesting their cotton.

Attention for irrigated wheat production was triggered with an attempt for off-season accelerated early generation seed production of stem rust resistant wheat varieties at Worer ARC initiated by the international Agricultural Research in the Dry Areas (ICARDA) and EIAR through the USAID supported wheat project in Ethiopia starting in 2008/09 cropping season. During the subsequent years, heat tolerant wheat varieties of ICARDA origin have been tested and released by EIAR and demonstrations and out-scaling of such heat tolerant wheat varieties have been carried out in the Afar and Oromia regions in partnership with EIAR, MoA, farmers, and private sectors through the Technologies for African Agricultural Transformation (TAAT) project supported by the African Development Bank (AfDB). Following these eye- opening activities along with the huge demand for wheat and need for import substitution, the government of Ethiopia has prioritized irrigated low land wheat production as key strategy to ensure national food security. To this end, in 2019 a plan has put in place to cultivate wheat in about 500,000 ha of available irrigable land along the Awash, Wabishebele and Omo rivers basins (Figure 1) in the coming 5 years [14]. In the year 2019/20, heat tolerant wheat varieties have been cultivated in about 21,000 ha along these three river basins under irrigation. In 2020/21, over 187,000 ha of land has been cultivated using heat tolerant wheat varieties in the same river basins. In the year 2021/22, more than 400,000 ha of wheat is being cultivated under irrigation across the entire country. The average yield level of the heat tolerant varieties under irrigation ranges from 4–7 t/ha. Motivated and encouraged with these achievements, the government of Ethiopia has set a plan to expand irrigated wheat production to a total of 1.5 million hactares in the coming 5 years. However, it is highly important to adopt modern irrigation schemes such as drip irrigation, raised bed plantings, crop rotation etc in order to minimize the risk of salinization and increase water use efficiency and productivity.

In the irrigated environments, wheat-rice, wheat-legumes, wheat-sesame or wheat-cotton rotation systems are practiced by growing wheat in the winter season. In the wheat-cotton rotation system, harvesting of cotton is delayed up to late October which pushes the wheat planting date to the last week of December. Such delayed planting of wheat exposes wheat to heat stress in March during grain filling period causing not only reduction in wheat yield but also reduction in wheat grain quality. Development and out-scaling high yielding and early maturing varieties of both crops is very important for the practical implementation of such double cropping system. Irrigated wheat production in the off-season in mid- and high-altitude areas could be affected by pre-harvest sprouting since most of these areas experience rainfall during March/April. Hence, it is highly recommended to map irrigated wheat production environments in the country and follow strict crop operation calendar so that double cropping is practiced, and maximum profitability of the system is achieved sustainably.

CHALLENGES TO WHEAT PRODUCTION

Wheat production in Ethiopia is constrained by several abiotic and biotic stresses at different levels of intensity across rainfed and irrigated environments. This is further heightened by increasing occurrence of climate change which is characterized by rising temperature (heat), less and erratic rainfall (drought) or sometimes excessive rainfall (flooding) and emergence of virulent pests and diseases [15–17]. The most important challenges for wheat production in Ethiopia are summarized below.

Biotic Stresses

The most important biotic constraints which affect wheat production in Ethiopia include diseases, insects and weeds. Rusts (*Puccinia* spp.), Helminthosporium, septoria (*Septoria tritici*), tan spot (*Pyrenophora tritici repentis*), fusarium (*Fusarium* spp.), as well as smuts, take-all, and root rots are important wheat diseases common in the highlands of Ethiopia. Associated with the current climate change effects, virulent stem rust strain of Ug99 and temperature tolerant yellow rust races have caused epidemics in Ethiopia [18]. Yellow (stripe) rust caused by *Puccinia striiformis* f. sp. *tritici* is the most prevalent and devastating disease in Ethiopia and other east African highlands. It has caused significant yield losses reaching up to 100% in the Ethiopian highlands as evidenced by the collapse of the dominant wheat varieties such as the semi-dwarf wheat variety Laketch in 1977; Dashen, a poplar high yielding variety with *Yr9* gene from 1B/1R translocation in1988 and in 1994; and in cultivar Wabe in 1998 [19,20]. Similarly, the two high yielding wheat varieties with *Yr 27* gene (Galema and Kubsa) were dominantly cultivated for more than 15 years until they became 100% susceptible in 2010 and banned from production.

Stem rust caused by *Puccinia graminis* f. sp. *ttritici* is prevalent in the low and mid altitude areas of Ethiopia with warmer temperature. It has knocked out major cultivars such as Enkoy with *Sr36* gene in 1994; and Digalu with *SrTmp*$^{+}$ gene in 2013 and 2014 resulting total crop failer [21]. The Digalu race (TKTTF) which is different from the Ug99 race (TKTTSK) is dominant across the major wheat growing regions of Ethiopia [21] and became a major threat to wheat production in the country.

Abiotic Stresses

In the rainfed environments, the most important abiotic stresses are drought, (especially in the lowlands), soil acidity, erosion, poor soil fertility, water-logging, and pre-harvest sprouting. Such constraints are most common in highlands of Ethiopia. The total rainfall in the wheat growing areas ranges from 600–1200 mm. Such problems are common in the high lands. The main problem associated with rainfall is not the total amount, but the uneven distribution which affects the crop production calendar, productivity and the grain quality when it rains at maturity stage of the crop (pre-harvest sprouting). Soil acidity is one of the most important constraints affecting about 6.3 million ha 43% of the arable land area in Ethiopia Efforts have been made to mitigate soil acidity through the application of liming. However, acid soils require large quantity of lime and it quickly become a very bulky affair as there is a need to apply 2 to 3 t/ha for sandy soils and up to 5 t/ha for clay and humifere soils [22].

Heat, salinity and inefficient use of irrigation water are the most important abiotic constraints in the irrigated environments. Germination of wheat within the grain head before harvest is called pre-harvest sprouting (PHS). It is a major problem both in rainfed and irrigated environments when there is prolonged rainfall at crop maturity before harvest. Such seed have a very poor rate of germination and hence it is not suitable for planting in farmers' fields. Furthermore, water absorption capacity and bread making quality of the flour from such sprouted wheat harvest is extremely poor as indicated by the 'falling number test' which measures alpha-amylase (an enzyme that breaks down starch within germinating seeds) activity within a grain sample[23]. Falling number (FN) tests are conducted by creating a slurry of flour and water in a test tube and measuring the time required in seconds for a weighted plunger to fall through the slurry. Wheat flour affected by PHS results in high α-amylase activity, low FN values (less than 250), poor rheological and cooking properties including poor quality for mixability, crumb strength, and loaf volume [23]. It is important to develop varieties with certain level of grain dormancy which are tolerant to pre-harvest sprouting. Wheat varieties with red seed coat grain have high level of dormancy and hence high level of tolerance for preharvest sprouting.

Limited Availability and High Price of Inputs

Wheat production in Ethiopia is dominated by subsistence farmers and its productivity is still very low partly due to the limited availability, accessibility and affordability of inputs such as fertilizers, improved seeds, irrigation water, pesticides and farm machineries [24]. Fertilizers are imported and hence the cost increases with the energy prices and global demands. Furthermore, accessibility for transportation and its cost along with access to credits affect timely distribution of fertilizers to farmers. Water availability and installation cost for irrigation schemes are limiting factors to expand wheat production in the irrigated environments. The irrigation schemes are along the main river basins (Awash, Wabe Shebele, Omo, and many other medium size rivers) which are filled through rains. Ethiopia has a huge rain water potential (estimated up to 1 trillion m^3) [24].The rivers are full to the maximum causing damage through excessive flooding during the summer (rainy season). The main challenge for the country is resource limitation to build dams, canals and related structures and facilities for modern irrigation schemes. The current furrow/flood irrigation system utilized by farmers is not effective and sustainable in terms of water use efficiency and controlling salinity.

Yield Gaps and Stagnation

Yield stagnation is the level where crop productivity reaches at its maximum ceiling due to genetic ceiling in the crop breeding programs, unfavorable factors such as biotic and abiotic stresses, climate change, and unproductive policies along the whole value chain. Some authors have attributed yield stagnation to the genetic ceiling in India and Europe while others have reported the presence of genetic gain in both spring wheat [25,26] and facultative winter wheat [27]. However, it is evident that the potential of new cultivars has not been fully utilized in most of the developing countries due to poor agronomic management, partial application of packages of inputs, reduced incentives and unstable market prices resulting in huge yield gaps. Fisher et al. [27] have reported wheat yield gap levels ranging from 26–69% at global level. However, the gap remains high especially in developing countries due to lack of knowledge and information reflecting on the performance of extension services and seeds/inputs delivery systems and poor infrastructures. In Ethiopia, progressive farmers could harvest 7t/ha under favourable rainfed environments and 8 t/ha under irrigated environments while the national average yield is about 3.1 and 4.4 t/ha under rainfed and irrigated environments indicating the presence of 44.3 and 55% yield gaps, respectively.

Infrastructure and Policies

Agriculture policies on: (1) land use and tenure (2) technology development, shopping, testing and adoption (3) subsidies (4) inputs marketing and distribution (5) taxation (6) infrastructure and human capital development (7) public-private-partnership, etc. do play significant roles in improving agricultural productivity, and social welfare development in Ethiopia. These policies should be flexible enough to accommodate improvements whenever needed to adapt changes within the country, regionally and globally. Low public and private investments, weak extension systems, weak market and infrastructure linkages etc. remains to be the major challenges for wheat production in Ethiopia [24]. Limited rural road networks and transportations not only limit access to agro-inputs (seeds and agro-chemicals) by farmers, but also limits aggregation, storge and transportation of wheat grain to markets. Shortage of power/energy affects development of agro-processing industries, irrigation schemes, and technology development. Therefore, it is important to unlock the key policy and regulatory challenges that constrain technology development, access and deployment; contract farming, innovative financing, public private partnership, and integrated wheat production, marketing and agro-processing for the success of the wheat industry in Ethiopia.

WHEAT BREEDING IN ETHIOPIA

Wheat research in Ethiopia was started since the 1930's through local germplasm collection and introduction of exotic germplasm. However, a formal wheat improvement program was started in 1949 at Pradiso government station, near Asmara, Eritrea and local and exotic germplasm were evaluated at this station for local adaptation and disease resistance which resulted in the release of durum (AlO, R18, P20 and H23) and bread wheat varieties of Kenyan origin (Kenya1, Kenya 5, Kenya 6) in the 1950's [9]. From 1953–1966, the Alemaya College of Agriculture (Debre Zeit Agricultural Experimental Station), Kulumsa station, Jima Agricultural and Technical School and the Extension Service of the Ministry of Agriculture continued wheat breeding, variety demonstration, seed multiplication and extension services. Agricultural research in Ethiopia was institutionalized and expanded since the establishment of the Institute of Agricultural Research (IAR) in 1966 with clear mandates, and responsibilities. Many national and regional agricultural research centers have been established from 1967 to 2000 with especial focus on coordination of key commodity research programs. The national wheat improvement program for bread wheat research is coordinated from Kulumsa ARC with research centers and testing sites located across the entire wheat growing regions of the country.

Germplasm, Acquisition, Development and Evaluation

Germplasm acquisition, primarily from the international agricultural research centers (IARCs) like CIMMYT and ICARDA, plays a monumental role in the success of the Ethiopian wheat breeding program. Elite germplasm has been introduced from two IARCs annually in the form of international nurseries and yield trials following standard material transfer agreement (SMTA) [7]. These elite germplasms should pass through the national quarantine procedures to make sure that it is free from alien pests followed by field evaluation at the national quarantine site at Kulumsa, Holeta, Adet and Sinana ARCs.

Hybridization (crossing) program is also carried out by the national breeding program at KARC. The pedigree selection method is used dominantly to manage the segregating generations (F2–F6). Selected genotypes both from the international and national nurseries (up to 100) are evaluated in the preliminary yield trials (PYT) for one year and the top performers (up to 25) are further evaluated in the national variety trials (NVT) or regional variety trials (RVT) for two years across representative locations in the country during which participatory variety selection involving farmers, pathologists, agronomists is carried out for vigor, biomass, plant height, resistance to diseases, earliness, yield potential, and farmers preference. The best 2–3 varieties are promoted to variety verification or registration trials (VVT). The overall germplasm development, acquisition and evaluation schemes is indicated in Figure 3.

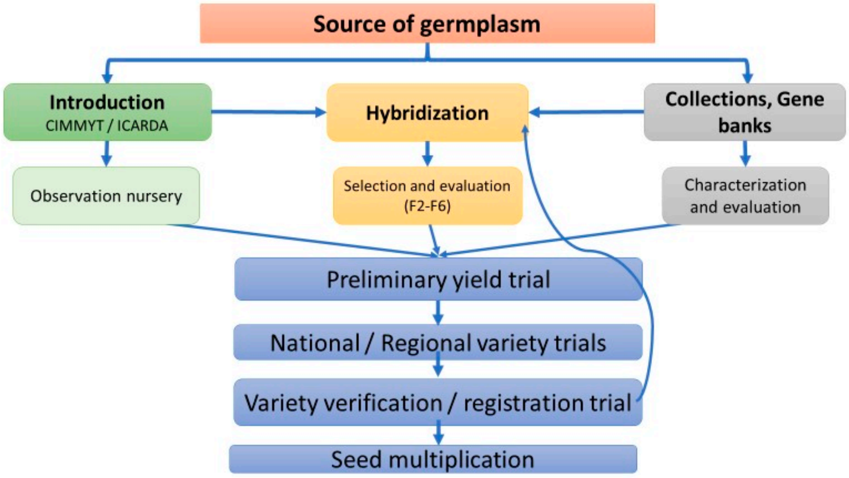

Figure 3. Variety development, evaluation and release scheme in Ethiopia.

Variety Release and Deployment

For variety release, at least the best 2–3 candidate varieties along with recent standard check and/or local farmer variety are tested under variety verification trial (VVT) for one year both on-station and on-farm in large non replicated plots of 100 m^2 (10 m × 10 m). It is to be noted that, before the VVT, the variety/yield trials should be carried out for two years in a minimum of 3 locations. The trial is managed by the respective wheat breeder. Evaluation is made by the technical committee assigned from Ministry of Agriculture (MoA) to undertake evaluation of the candidate varieties at grain filling stage for resistance to diseases, maturity, yield potential and farmers' preference. The technical committee reports its assessment to the national variety release committee including mostly breeders from NARS (agricultural research institutes, universities) and Plant Variety Registration and Protection Directorate of MoA. The committee, based on evaluation of the NVT/RVT data, and reports of the technical committee which includes farmers assessment, makes decision to release, reject or repeat the variety. Up on release, 50–100 kg of breeder seed should be submitted to the national/regional seed enterprises for multiplication of pre-basic, basic and certified seed. Following this procedure, the Ethiopian Agricultural Research Institute has released more than 80 bread wheat varieties to-date. However, only few of the varieties such as Lakech (PJ/GB55 or PENJAMO-62(SIB)/GABO-55) released in 1970, Enkoy (HEBRAND SAL/WIS24/SUP51/(FR/FN/Y) and Dereselign (CI8154/2*FR) released in 1974, ET13-A2 (Enkoy/UQ105) released in 1981, Pavon 76 (VICAM-71//CIANO-67/SIETE-CERROS-66/3/KALYANSONA/BLUEBIRD) released in 1982; Dashen (KVZ/BUHO//KAL/BB or AVKAZ/(SIB)BUHO//KALYANSONA/BLUEBIRD) released in 1984, Kubsa (ND/VG 9144//KAL/BB/3/YACO/4/VEE or NORD-DESPREZ/VG-9144//KALYANSONA/BLUEBIRD/3/YACO/4/VEERY) and Galema (4777*2//FKN/GB-AUS/3/PV or 4777*2//FKN/GABO/3/PAVON-76) released in 1995, Madda Walabu (TL/3/FN/TH/NAR59*2/4/BOL'S') released in 2000, Digalu (SHA7/KAUZ) released in 2005 have been grown widely [7]. Some of the cultivars such as Dashen which originated from the VEERY cross (KVZ/BUHO//KAL/BB) and Kubsa from the Attila cross (ND/VG9144//KAL/BB/3/YACO/4/VEE#5) have been also released and grown as mega cultivars with different local names across many countries. Many wheat varieties with resistance to Ug99 and heat tolerance have been released by the national program from CGIAR(CIMMYT/ICARDA) origin elite germplasms [7,28,29].

Recurrent rust epidemics remain the major driver for bread wheat varietal change in Ethiopia. Massive wheat scaling projects implemented by ICARDA and CIMMYT in partnership with EIAR led to dramatic changes where old rust susceptible wheat varieties such as Kubsa were replaced with newer rust resistant wheat varieties. The availability of functional and robust seed system is very important to multiply seeds of new improved varieties sufficiently with well-defined marketing and distribution schemes. There is a time lag between wheat variety release and availability of certified seed in farmers' fields principally due to lack of commercialization strategy, the limited capacity of the seed sector, the low multiplication factor and large quantities of seed required for planting and the poor infrastructure for marketing and transportation [30]. Very low rate of variety replacement (more than 10 years) and annual seed renewal rate which is measured by farmers regular purchase of certified seed (less than 20%) have been reported [28]. It is therefore important to strengthen the seed system in Ethiopia through capacity development, formulating and implementing stable policy frameworks, encouraging participation of private sectors through incentives, and improving the marketing, information and transportation infrastructures.

Table 1. List of selected cultivars with noticeable impacts and recently released varieties in Ethiopia (1974–2021).

SN	Variety name	Pedigree	Origin	year of release
1	Enkoy	EBRAND SAL/WIS24/SUP51/(FR/FN/Y)	CIMMYT	1974
2	Dereselign	CI-8154/2*FR	CIMMYT	1974
3	K-6290 Bulk	AFM/2*ROMANY	CIMMYT	1977
4	K6295-4-A	ROMANY x GB-GAMENYA	CIMMYT	1980
5	ET-13-A2	ENKOY/UQ105	CIMMYT	1981
6	Pavon-76	VICAM-71//CIANO-67/SIETE-CERROS-66/3/KALYANSONA/BLUEBIRD	CIMMYT	1982
7	Dashen	KAVKAZ/(SIB)BUHO//KALYANSONA/BLUEBIRD	CIMMYT	1984
8	Mitike	OW 28/ROMANY BC	CIMMYT	1994
9	Kubsa	NORDDESPREZ/VG9144//KALYANSONA/BLUEBIRD/3/YACO/4/VEERY	CIMMYT	1995
10	Wabe	MAIORAL/BUCKBUCK	CIMMYT	1995
11	Galema	4777*2//FKN/GB-AUS/3/PV	CIMMYT	1995
12	Madda Walabu	TL/3/FN/TH/NAR59*2/4/BOL'S'	ICARDA	1999
13	Bobicho	PEREGRINE/PF70354/4/KALYANSONA/BLUEBIRD//ALONDRA/3/MARINGA	CIMMYT	2002
14	Digalu	SHANGHAI-7/KAUZ,MEX	CIMMYT	2005
15	Millennium	ALONDRA/CEP75630//CEP75234/PAT7219/3/BUCKBUCK/BIY/4/	CIMMYT	2007
16	Kakaba	KIRITATI/SERI/RAYO	CIMMYT	2010
17	Danda'a	KIRITATI//2*PBW65/2*SERI.1B	CIMMYT	2010
18	Hoggana	PYN/BAU//MILAN (= ETBW 5780	ICARDA	2011
19	Shorima	UTQE96/3/PYN/BAU//Milan	ICARDA	2011
20	Hidase	YANAC/3/PRL/SARA//TSI/VEE#5/4/CROC-1/AE.SQUAROSA(224)//OPATTA	CIMMYT	2012
21	Ogolcho	WORRAKATTA/2*PASTOR	CIMMYT	2012
22	Hulluka	UTQUE96/3/PYN/BAU//MILAN,	ICARDA	2012
23	Lucy	SKAUZ/BAV92/3/CROC-1/AESQUARROSA (224)//OPATA;	ICARDA	2013
24	Adel 6	SAMAR-13/PASTOR-1;	ICARDA	2013
25	Honqolo	NJORO SD-7 (NJORO SD-7//VEE/NAC	ICARDA	2014
26	Biqa	(PASTOR//HXL7573/2*BAU/3/WBLL1)	ICARDA	2014
27	Amibara	SHUHA-8/DUCULA	ICARDA	2015
28	Dambal	AGUILAL/3/PYN/BAU//MILAN= AGUILAL/FLAG-3	ICARDA	2015
29	Fentale)	FERROUG-2/FOW-2	ICARDA	2015
30	Obora	UTIQUE96/FLAG-1	ICARDA	2015
31	Wane	SOKOLL/EXCALIBUR	CIMMYT	2016
32	Lemu	WAXWING*2/HEIL0	CIMMYT	2016
33	Dursa	NAVJ07/SHORTENED	CIMMYT	2020
34	Boru	SAUAL/MUTUS/6/CNO79//PF70354/MUS/3/PASTOR/4/BAV92*2/5/FH617/7/CNO79//PF70354/MUS/3/PASTOR/4/BAV92*2/5/FH6-1-7	CIMMYT	2020
35	Abay	BOUSHODA-1/4/CROC-1/AE.SQUARROSA(205)//KAUZ/3/ SASIA	ICARDA	2021
36	Shaqi	BABAX/LR42//BARAX/3/ER2000/4/BAVIS	CIMMYT	2021

Genetic Gains and Breeding Progress

The wheat breeding program in Ethiopia, like the many other breeding programs in the developing world, has been relying on germplasm acquisition from the IARCs (CIMMYT and ICARDA) followed by rigorous evaluation for regional/national adaptation and resistance to biotic and abiotic stresses. A total of 88 bread wheat varieties originated from CIMMYT and ICARDA were released to-date. List and pedigree of the most important varieties is indicated in Table 1. Only some of the varieties became successful cultivars. As indicated in Figure 4, there has been a continuous increment in yield (39.3 kg ha^{-1} year^{-1}) which is in line with the previous report by Girma et al. [31] who reported annual increase of 23 kg ha^{-1}year^{-1}. The amount reported in this review is almost twice as much in comparison to the previous study, as yield data obtained at the time of variety registration was utilized here, whereas an assessment of the actual genetic gain would require testing all released varieties in a common trial. The average yield of released varieties increased from 2 t/ha in variety Lakech released in 1970 to almost 6.5 t/ha in the variety Abay released in 2021.

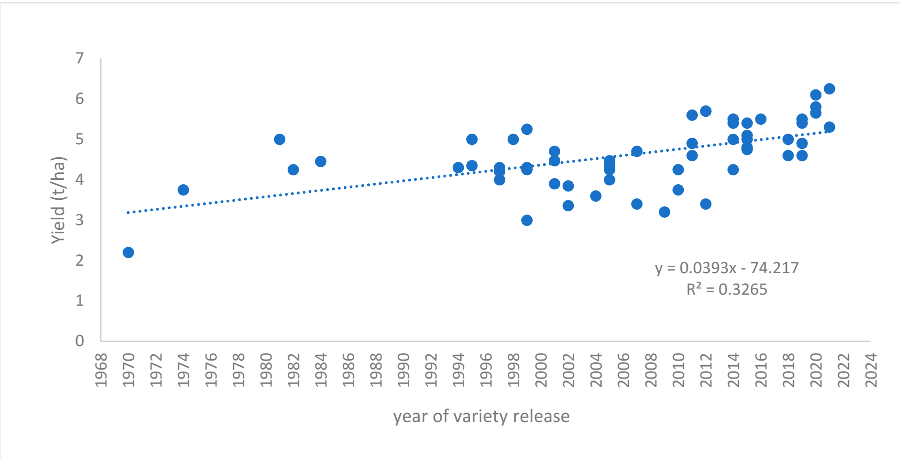

Figure 4. Progress in grain yield of bread wheat varieties released in Ethiopia: 1970–2021.

The progress in grain yield is a direct reflection of the breeding progress achieved at the level of the IARCs. Genetic gain studies at CIMMYT and ICARDA have shown a steady progress for yield, disease resistance and improvement in grain quality [7,26,32,33]. The genetic gain studies for the ICARDA's spring bread wheat program across key locations indicated that yield levels of the current top yielding elite genotypes reached up to 6 t/ha at Wadmedani station of Sudan under extreme heat stress, 7 t/ha at Merchouch station of Morocco under terminal moisture stress (260–300 mm) and 11 t/ha at Sids station in Egypt under optimum irrigated conditions. Genetic gain analysis from 1980 to 2017 showed an increase of 2.5, 1.3 and 2.3% year^{-1} at Merchouch (Morocco), Wadmedani (Sudan) and Sids (Egypt) stations, respectively [7]. The annual genetic gain in Ethiopia is low as compared to other countries. This is due to the prevalence of severe biotic (yellow rust, stem rust, septoria) and abiotic (terminal moisture, soil acidity etc.) stress across most locations in the mid- and high-altitude areas where wheat is grown under rainfed conditions.

The rate of variety replacement in Ethiopia was very high mainly due to the rapid breakdown of resistance to rusts (yellow and stem rust). This is associated with the co-evolution of the pathogen and the host which along the conducive environment favours high mutation rate of rust pathogens. The development and deployment of resistant varieties based on single gene resistance approach has resulted to the rapid break down of resistance due to the emergence of new strains of the pathogen with a recurring cycle of ‘boom-and-bust’ in cultivar performance. This has been clearly documented by the breakdown of the *Yr9* gene in the cultivar Dashen in Ethiopia and in all other cultivars derived from the same ‘Veery’ cross in the 1980’s across the CWANA region. Similarly, the breakdown of *Yr27* gene in the year 2000’s in the major wheat cultivar ‘Kubsa” in Ethiopia and other similar mega cultivars derived from “Attila” cross such as PBW343 (India), Inquilab-91 (Pakistan), and other cultivars from different pedigree such as Achtar in Morocco, Hidab in Algeria and many other cultivars in the Central and West Asia and North Africa (CWANA) region has caused significant loss in wheat production [18]. Recently, a new stem rust race Ug99 (TTKSK) has been first detected in Uganda in 1999 and then spread to Kenya, Ethiopia, Yemen, Sudan and Iran, and became a global threat to the wheat industry of the world for the very fact that it overcomes many of the known and most common stem rust resistance genes such as *Sr31, Sr24 and Sr36* [31,34]. In Ethiopia, *Sr24* is still very effective, and among the Yr genes, *Yr5, Yr15, Yr32* and *YrSP* are still highly effective [21]. In most developing countries, apart from grain yield and disease resistance, grain quality was not a strong criterion of variety selection. However, demands are changing overtime and some NARS in developing countries are critically looking for better quality varieties suited for the preparation of different wheat end products. Wheat varieties such as Bezostaya, Achtar, Veery, HD1220, and Pavon-76 are known for their excellent grain quality. These varieties are still dominantly grown in some countries not only because of their wide adaptation, high yield potential and stability but also because of their high protein content and quality. Cognizant of this the wheat breeding programs at CIMMYT and ICARDA undertake evaluation of germplasm for quality traits following standard grain quality procedures. Most of the currently available elite genotypes for both irrigated and rainfed environments are excellent in quality with protein levels of 12 to 16%. Most of these genotypes have the 5 + 10 (Glu-D1), 7 + 8 (Glu-B1) and 2* (Glu-A1) alleles. These alleles, especially the 5 + 10 Glu-D1 allele, have been reported to be highly correlated with protein quality and are being used intensively as a selection criterion in wheat breeding for improving end-use quality [35,36].

FUTURE PROSPECTS

Wheat consumption in Ethiopia has increased over years due to population increase, change in food habits and rapid urbanization, causing a huge gap between local wheat production and demand which in turn forces the country to rely on import by incurring millions of dollars from its annual budget. However, the option of importing wheat is not always easy and reliable as it depends on the availability of wheat in the global market, ability to compete and buy on time where there is a price-shock due to low production of wheat at global level as exemplified in 2008 and 2010 associated with climate change effects (occurrence of severe heat and drought stresses, aggressive diseases and pests) and currently associated with the Ukraine-Russia crisis in 2022. During such crisis, even countries which have the money to buy at any cost might have no access because of the export ban by the wheat producing countries. Recent studies on the profitability and potential of wheat production in Africa indicated that Ethiopia has huge potential to grow wheat both under rainfed and irrigated production systems for both local consumption and export purposes. There is a huge potential to increase wheat production in Ethiopia both vertically and horizontally. The recent expansion of irrigated wheat production from almost none in 2015 to 500,000 ha in 2022 is a very good example of horizontal expansion. The future growth of wheat production in Ethiopia is expected to come from use of climate smart/resilient varieties (tolerant to heat, drought, salinity; acidity, pre-harvest sprouting, nutrient and water use efficient); area expansion, lime application, integrated crop management (mechanization, fertigation, chemicals for pest control); and genetics (hybrid wheats, super wheats (climate smart, organic wheats) etc.) as indicated below in Figure 5. However, the following recommendations should be implemented carefully in the short, medium term and long-term periods for sustainable wheat production while conserving the natural resource base.

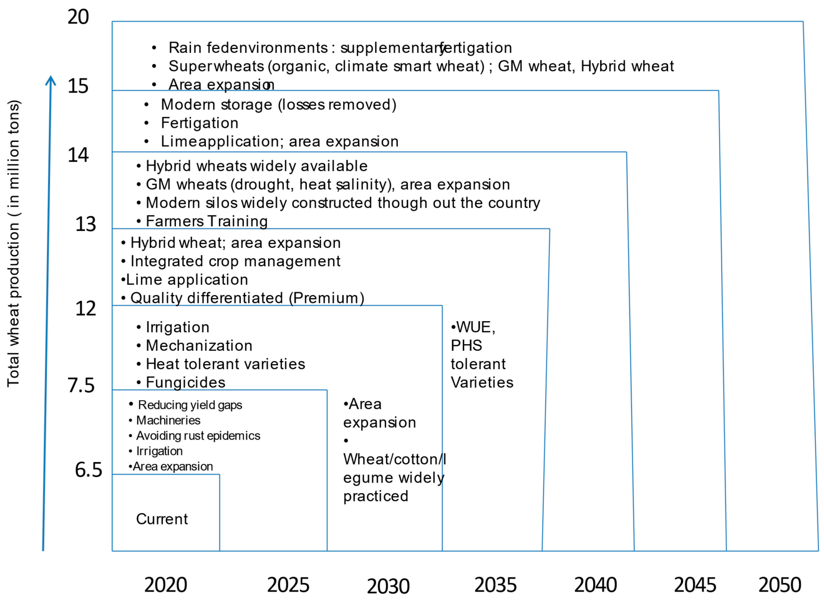

Figure 5. Wheat Futures in Ethiopia.

Rapid Variety Development Through Strong National Shuttle Breeding Program Using Kulumsa and Worer Research Stations

The wheat breeding program in Ethiopia like many other developing countries depends totally on the germplasm supply from the IARCs (CIMMYT and ICARDA). The IARCs are there to support national programs both in germplasm development and capacity development so that the national programs will be able to develop and deploy varieties specific to the different agro-ecologies of the country rapidly and efficiently with accelerated genetic gain. To this end, the national wheat breeding program of Ethiopia coordinated by Kulumsa ARC should establish a strong shuttle breeding program (Table 2) where by the simple and top crosses are carried out in the plastic/greenhouses at Kulumsa, F2 generations are planted in large plots of 10 m length six row plot at Kulumsa during the main season (summer) and F3 generations are planted in November/December in plots of 2.5 m length with six rows at Worer and selected spikes are harvested for head rows planting in the summer at Kulumsa. The preliminary yield trials (PYT) are planted in November/December at Werer and harvested in March/April. The National Variety Trials (NVT) will be planted during the main season (summer) across the different key locations for rainfed environments and in November/December across irrigated key locations for consecutive two years across the country. The top performing varieties across the key locations/regions should be included in the variety verification trials (VVT) for regional/national release based on adaptation following the national variety release schemes.

Table 2. Rapid shuttle breeding scheme for wheat in Ethiopia.

Year	Generation	Location	Season
1	Crosses (simple, F1 top)	Kulumsa (greenhouses)	Summer and winter
2	F2	Kulumsa	Summer (June–october)
	F3	Worer	Winter (November–March)
3	F3:F4 head rows	Kulumsa	Summer (June–October)
	PYT	Worer	Winter (November–March)
4	NVT (1st year)	rainfed key locations	Summer (June–October)
		irrigated locations	Winter (November–March)
5	NVT (2nd year)	rainfed key locations	Summer (June–October)
		irrigated locations	Winter (November–March)
6	VVT	rainfed key locations	Summer (June–October)
		irrigated locations	Winter (November–March)

This shuttle breeding program could be utilized for germplasm development and supply for the whole of Africa as the Kulumsa ARC was previously selected as Wheat Center of Excellence for SSA. To this end, it is important that the AfDB as a main proponent of Feed Africa where wheat is one of its commodity flagships together with the respective national MoA, NARES and other stakeholders to uphold this vision and promote the KARC as Africa's Wheat Research Center following the modalities of the Africa Rice.

Access to Improved Seeds, Fertilizers and Machineries

Development and release of improved varieties is not an end by itself unless these varieties are multiplied and marketed to farmers efficiently and timely and make impact on the livelihoods of farmers. To this end, establishment of robust seed system which enables production of early generation seeds (breeder, pre-basic, basic), certified seed and efficient marketing systems with strong infrastructure and policy and legal frameworks is crucial [28].

Application of chemical fertilizers (DAP, urea etc.) have significantly increased wheat production. However, the increase in price and issues associated with their limited availability are becoming huge challenges to farmers and governments alike. Establishment of fertilizer processing plants within the country should be a priority to increase agricultural productivity in the country sustainably. Similarly, the lack of machineries (tractors, planters, harvesters etc.) is a key impediment for the progress of Ethiopian agriculture. The continuous shallow ploughing of the land by local tools using oxen power has exposed the topsoil to leaching/erosion resulting in soil acidity. Land ploughing by tractors helps deep ploughing, better pulverization and improves water holding capacity. The current flood irrigation scheme under flat conditions utilizes much water and exposes the soil for salinity. The use of raised bed planting, crop rotation and drip irrigation schemes should be promoted in the irrigated environments of the country to save water, reduce salinity, weeds and improve productivity. The harvesting and threshing operation using animal powers is also time consuming and results in crop losses. According to Ferris S. and Wheatley C. [35,37], the average post-harvest losses of food crops such as Teff, Sorghum, Wheat and Maize due to unsuitable post- harvest management employed are 12.9%, 14.8%, 13.6% and 10.9% respectively. It is therefore critical to promote production and scaling of agricultural machineries through private and public partnership in order to increase their accessibility and affordability.

Application and Utilization of Integrated Crop Management Practices

The prevalence of diseases and pests especially in the highlands of Ethiopia is a major limiting factor to wheat production. Development and deployment of varieties with resistance to the major diseases (rusts, septoria, fusarium etc.) is environment friendly and socially and economically feasible solution to control wheat diseases. However, the resistance of varieties collapses shortly after its deployment especially when the resistance of the varieties is due to single major gene. In this regard, it is important to pyramid 2 or more major genes on minor gene background using molecular markers and key location testing approaches to develop varieties with durable resistance. Furthermore, it is important to diversify varieties grown in each of the agro-ecologies to reduce risk of total crop loss and avoid the boom-and-bust cycle of pathogen development across large areas at a time. Development and deployment of an Integrated Pest Management (IPM) approach is recommended as a sustainable approach for the control of diseases and pests while conserving the natural resource base. Most wheat growing countries in the developed world use one time application of general fungicides before the presence of any diseases and it has been reported that such practice has significantly increased yield. Similarly, Ethiopian wheat farmers should spray general fungicide (Propiconazole at the rate of 0.5 L/ha) to protect their wheat crop against diseases and lower the inoculum build up and slow down mutation rates of pathogens.

Establishment and Promotion of Commercial Agriculture

Ethiopian agriculture is predominantly carried out by smallholder farmers and subsistence in nature hence less capital intensive. On the other hand, there are some commercial farms by entrepreneurs with reasonably large investments. One of the major reasons for the limited presence of commercial agriculture in Ethiopia is the land ownership policy. However, the government policy allows investors to lease land for up to 25 years and there are incentives to invest on agriculture including access to loans, tax exemption for up to 5 years, and duty-free import of machineries. Such lands for investment are available dominantly in the lowlands where still there are limitations in infrastructure such as roads, electricity, irrigation schemes and social service facilities. The government is expected to encourage entrepreneurship in agriculture by providing the necessary infrastructure and services.

Ethiopians especially agricultural professionals should learn from past experiences of their colleagues who pioneered private farms and the current private banking sector and form joint ventures in establishing commercial farming, seed companies, milling industries and bakeries by involving millions of shareholders to mobilize resources. Such tangible efforts will enable to modernize the agricultural sector and will increase productivity, create jobs and wealth, substitute imports, ensure food security and self-sufficiency to avoid dependency on food aid and imports.

AUTHOR CONTRIBUTIONS

WT: Developed the first draft; HZ, DK, WS, TS, TN, TD, NG, ZB, SA contributed in the writeup and review of the manuscript.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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