 doi:10.20944/preprints201904.0149.v1

Durum wheat (*Triticum durum* Desf.) origin, cultivation, and potential expansion in sub-Saharan Africa

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Received: date; Accepted: date; Published: date

Abstract

Durum wheat is an important food crop in the world and an endemic species of sub-Saharan Africa (SSA). In the highlands of Ethiopia and the oases of the South Sahara this crop has been cultivated for thousands of years. Today, smallholder farmers still cultivate it on marginal lands to assure production for their self-consumption. However, durum wheat is no longer just a staple crop for food security but it has become a major cash crop. In fact, the pasta and couscous industry currently purchase durum grain at prices 10 to 20% higher than bread wheat. Africa as a whole imports over € 4 billion per year of durum grain to provide the raw material for its food industry. Hence, African farmers could obtain a substantial share of this large market by turning their production to this crop. Here, the achievements of the durum breeding program of Ethiopia are revised to reveal a steep acceleration in variety release and adoption in the last decade. Furthermore, the variety release for Mauritania and Senegal is described to show how modern breeding methods could be used to deliver grain yields above 3 t ha^{-1} in seasons of just 92 days

 doi:10.20944/preprints201904.0149.v1

of length and daytime temperatures always above 32°C. This review describes the ability of releasing durum wheat varieties adapted to all growing conditions of SSA, from the oases of the Sahara to the highlands of Ethiopia. This potential area of expansion for durum wheat production in SSA is not linked to any breeding technology, but rather it remains dependent on the market ability to purchase these grains at a higher price to stimulate farmer adoption. The critical importance of connecting all actors along the semolina value chain is presented in the example of Oromia, Ethiopia, and that success story is then used to prompt a wider discussion on the potential of durum wheat as a crop for poverty reduction in Africa.

Key words: Agro-industry, Ethiopia, oasis wheat, pasta wheat, Senegal River, value chain

1. Introduction

Durum wheat (*Triticum durum* Desf.) is an important food crop of the world, with an estimated 36 million t of annual global production [1]. The largest producing countries are Turkey and Canada with estimated 2 million ha each [2-3], followed by Algeria, Italy, and India, each cultivating over 1.5 million ha [4-6]. Syria belonged to this group of large producers, but the recent unrest has strongly reduced crop production. France, Greece, Morocco, Pakistan, Portugal, Kazakhstan, Russia, Spain and Tunisia cultivate durum wheat on between 0.5 and 0.8 million ha annually [3]. Azerbaijan, Iraq, and Iran combined grow durum wheat on over 0.7 million ha [6]. In addition, Egypt, Jordan, and Lebanon cultivate it on relatively large areas [7-9]. The Sonora desert and other small areas of Mexico also target the production of this crop for the export market on an area of approximately 0.2 million ha [10]. Australia is similarly exploring the cultivation of this crop with 0.1 million ha allocated annually to its production [11]. In sub-

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Saharan Africa (SSA), Ethiopia is the largest producer of durum wheat, with approximately 0.6 million ha [12].

A very large amount of genetic diversity exists for this crop, and that diversity also extends to the many traditional ways of consuming it, including several unique dishes that represent with pride the national identities: pasta, couscous, *bourghul*, *freekeh*, *gofio*, and unleavened breads, just to name a few [13]. Regardless of its tight connection to the dishes of the tradition, durum wheat today is cultivated in developed countries mainly as a cash crop to feed the booming pasta and couscous industry. The annual production of pasta was estimated at 14.3 million t in 2013, with a global market approximated at €14.9 billion and average global price of 1,045 € t^{-1} [14]. On a global scale, most of its consumption and production are in Europe, South America, and the United States of America. Africa accounts only for 5.6% of total pasta production, mainly in Egypt, South Africa, and Tunisia [14], and Asia consumption is also on the raise. Detailed data for SSA are hard to obtain, as most statistics combine durum wheat with bread wheat into single "wheat" data points, but the estimations that could be gathered from several sources suggest an import market of € 337 million, and an export market mostly within the continent of € 40 million (**Table 1**). Reliable data on the size of the internal market were not found. In this review, the developing couscous industrial market is not included, as data are not readily available. Italy, North African, South Africa, and Turkey are the largest exporters of pasta to SSA [15]. However, the total area dedicated to durum wheat in SSA is limited to 630,000 ha, of which 90% is cultivated in Ethiopia. Therefore, this is the only country capable of producing pasta using locally grown grain, while for all other SSA countries the bulk of pasta production required the import of € 483 million worth of durum grain from Canada, Turkey, and the USA (**Table 1**). It

 doi:10.20944/preprints201904.0149.v1

must be mentioned that the pasta industry in SSA often utilizes bread wheat flour for its production, and typically only products from North Africa and developed countries meet the international standard of 'pasta' by using 100% durum semolina [14]. Clearly, there is huge agricultural and commercial scope for expanding domestic production and marketing of durum wheat in SSA countries.

Durum wheat and rice are the most lucrative among the cereals, with prices usually 20 to 40 % higher than common wheat, millet, maize, and sorghum [16]. While durum wheat remains a critical staple food for smallholder farmers in marginal lands, thanks to its exceptional adaptation to climatic stresses, its large-scale production is tightly linked to its greater monetary return. In the absence of governmental subsidies that push toward the cultivation of other crops, farmers tend to prefer durum wheat as long as the market continues to guarantee additional profits. In this regard, the existence of a strong value chain for the pasta, couscous, and *bourghul* industry is quintessential to the success of durum wheat cropping.

In this review, the current status of durum wheat production in SSA is discussed in comparison to the needs of the local pasta industry to better understand the potential of its expansion through the deployment of novel adapted varieties. Because of its industrial nature, durum wheat has often been disregarded by SSA policy makers in favor of bread wheat as a more direct food source. However, among the sustainable development goals set by the United Nations, "poverty reduction" is considered as a strategic way to tackle famine, without causing nutritional deficits due to mono-food diets. In this sense, durum wheat is at least as well suited as bread wheat in

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improving livelihoods. Both aspects of durum wheat, as a "food security" staple food for smallholder farmers, as well as a "poverty reduction" industrial crop will be considered here.

2. An endemic crop of SSA: durum wheat second center of origin in Ethiopia

Durum wheat originated from the domesticated form of a wild species named emmer wheat (*Triticum dicoccum* Koern.*)* between 12,000 and 10,000 years ago, in the West Levantine [17]. Phoenicians have traded it along the Mediterranean shores since historical times and throughout the rise of civilizations this crop has encountered several waves of expansion until today's global importance [18]. However, durum wheat did not originate solely in West Asia. Archeological evidence suggests that naked emmer reached Ethiopia approximately 5,000 years ago [19], probably arriving from the Levantine, through Egypt, along the Silk Road [20]. Today emmer wheat occupies approximately 7% of the wheat production in Ethiopia under the local name of *aja*. Recent molecular data [21] indicated that Ethiopian farmers repeated what had been achieved already in West Asia before, by deriving durum wheat anew through the further domestication of emmer. This new origin of the same crop gave rise to a subspecies known as *T. turgidum* ssp. *aethiopicum* or *abyssinicum*. Until relatively recently, landraces belonging to this subspecies were widely cultivated by smallholder farmers in Ethiopia, with up to 80% of the total durum land farmed with these unique biotypes [22]. The highlands of Ethiopia are known areas of rich biodiversity, and durum wheat is no exception [23-24]. For instance, one of the unique characteristics identified among *T. aethiopicum* landraces is a purple color of the grains, particularly rich in anthocyanins [25]. Anthocyanins, as anti-oxidants and with other health benefits, could be potentially exploited by the pasta industry to develop extra nutritious food products. Morphological and molecular characterization of these landraces has only just begun,

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and already several traits such as resistance to diseases (e.g., stem rust, powdery mildew), drought tolerance, long coleoptile, high tillering and resistance sources to Hessian fly have been identified [26-27]. This biodiversity has already started attracting strong interest by the international community for utilization, pushing the Ethiopian Government to protect it under strict germplasm exchange policy [28]. In order to conserve these resources, the Ethiopian Biodiversity Institute (EBI) has established a holding of over 7,000 accessions collected from different parts of Ethiopia [22]. These collections have been extensively investigated for their morphological and molecular diversity by many researchers, and useful traits were identified and are utilized by breeders and plant genetic conservationists in Ethiopia and beyond [29-37]. In the past two decades, the acreage of traditional tetraploid wheat has drastically diminished due to displacement by improved bread wheat varieties, extensive cultivation of *Tef* and Kabuli chickpea, farmland fragmentation, policies favoring bread wheat, and the absence of local seed supply systems [38]. To reduce this genetic erosion, EBI has established *in situ* conservation sites to conserve the agro-biodiversity at the farm level in different parts of Ethiopia. Community biodiversity practices were established in East Shoa and South Wollo zones with the aim of establishing community seed banks, participatory variety selection and re-introduction of local durum wheat cultivars, food legumes and sorghum into the cropping system [39-40]. Regardless of their specific uses, these landraces represent a treasure chest of potentially new and useful traits that breeders could be able to exploit to deliver superior varieties with added market values.

3. Durum wheat in East Africa as a staple and cash crop

East African countries cultivate almost 2 million ha of wheat, of which only 630,000 ha are farmed with durum wheat (**Table 2**). Eritrea, Kenya, Somalia, and Sudan combined harvested as

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146 little as 37,000 ha of durum wheat in 2014. Yet, these countries have maintained in their culinary
147 taste the influence of the past Italian presence in the region, with pasta imports reaching 40
148 million USD in 2017 in Ethiopia only. In the case of Kenya, national production is sufficient to
149 support the export of € 0.5 million worth of pasta and durum grain.
150
151 The durum varieties used for production are old bred-lines from Centro Internacional de
152 Mejoramiento de Maíz y Trigo (CIMMYT) and International Center for Agricultural Research in
153 the Dry Areas (ICARDA) such as 'Mwewe' (Flamingo/Leads), Mindum XA10
154 (Mindum/Asmara 10), and Sham 1 (Plc/Ruff//Gta/Rtte), in Eritrea, Kenya, and Sudan,
155 respectively (**Table 2**). The most critical traits of these varieties are earliness and tolerance to
156 heat in irrigated Sudan, and resistance to rust diseases under rainfed cultivation in Eritrea and
157 Kenya. Information from Somalia is scarce and hard to obtain. Considering that the most
158 cultivated durum varieties listed above are more than 30 years old, there is a significant genetic
159 yield gap that could be filled through the release and commercialization of more modern
160 varieties.
161
162 The Ethiopian case is presented in some detail, including critical historical steps, as it provides
163 valuable lessons for other SSA countries planning to grow their durum wheat sector. In Ethiopia,
164 durum wheat is produced predominantly in Gojam, Gonder, Shewa, Tigrai, and Wollo regions
165 [41]. The main growers are smallholder farmers in the highlands, where the environmental
166 characteristics are relatively low temperatures and high rainfall on black swelling/shrinking
167 vertisol soils, with water logging as a common problem. The crop is planted late in the growing
168 season to avoid early water logging and it continues to grow during the dry period on residual

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moisture at altitudes between 1800 and 2800 m.a.s.l. [33]. Due to late planting it forfeits some of its additional potential yield, in favor for higher protein content. The crop is consumed in several different forms such as unleavened breads, pancakes, macaroni and spaghetti, biscuits and pastries. The most common of the Ethiopian and Eritrean recipes are *dabo* (Ethiopian home-made bread), *hambasha* (bread from northern Ethiopia), *kitta* (unleavened bread), *injera* (thin bread normally made with *Tef*), *nifro* (boiled whole grains), *kolo* (roasted whole grains), *dabo kolo* (round and seasoned dough), and *kinche* (crushed kernels, cooked with milk or water and mixed with spiced butter). Besides the role of grain in traditional food and processed products, durum wheat straw is also greatly appreciated for its high palatability for livestock in the mixed farming systems of the highlands of Ethiopia [42]. Ethiopia today cultivates 562,000 ha of durum wheat [12], accounting for the vast majority of the cultivation of this crop in SSA (**Table 2**). Still, today's value represents just half of the land that was dedicated to durum wheat in 1967 [43], and this reduction continues in favor of more extensive farming of bread wheat [44].This is the combined result of political will, the introduction of modern bread wheat cultivars that have replaced the traditional durum wheat landraces, and the absence until now of vocal local industry demand of high quality pasta made from durum semolina. Ethiopian's push toward bread self-sufficiency has resulted in a monoculture of bread wheat (as well as maize), often cultivated in both the long (*meher*) and short (*belg*) rainy seasons, which in turn created a favorable environment of continuous host presence for the spread of damaging rust diseases and for the surge of tenacious weeds [45-46]. Tef, the largest cultivated crop in Ethiopia, also contributes to an increasing monoculture nature of Ethiopian agriculture.

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Durum wheat research in Ethiopia started back in 1949 at the Paradiso Experimental Station near Asmara [47]. Among several local durum landrace collections tested for productivity, and stem and leaf rust resistance, four selections (A10, H23, P20, and R18) were developed and released to farmers in Eritrea in 1952. In 1956 and 1957, several crosses were made between local and exotic varieties mainly for the purpose of transferring the stem and leaf rust resistance of A10 and R18 to cv. 'Mindum' from the USA (**Table 2**). This resulted in two new varieties, which unfortunately had to be rapidly retracted due to susceptibility to new leaf rust races [48]. In the 1980s, the wheat research activities at the Paradiso station were discontinued, and durum wheat breeding was transferred to the Debre Zeit Agricultural Research Center [31]. At the Center, many cultivars were developed and released, derived from landrace selections, local crosses and introductions from the international durum wheat breeding programs at CIMMYT and ICARDA. For clarity, in this review the word 'cultivar' has been used to define germplasm cultivated on large amounts of land, while the word 'variety' is reserved to define germplasm officially registered in the variety catalog of one country. The first durum cultivars released from local breeding selections were 'Arendeto' (DZ04-118) and 'Marou' (DZ04-688), obtained by mass selection [49]. These were followed by the varieties 'Cocorit-71', 'LD-357' and 'Gerardo' obtained from the international agricultural research centers. Since 1982, a formal variety release system has been put in place, which rationalized also the previous work into a variety catalog, which accounts today for 40 durum wheat cultivars (**Fig. 1**). In the last two decades, many federal and regional agricultural research centers have become involved in durum wheat improvement to respond to the demand by 300 local flour and pasta manufacturers as well as the local consumers. This push by the national food industry, combined with a stronger presence in the region of international development agencies involved in breeding against the emerging

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Ug99 stem rust race threat [50], has resulted in an increase in the release of durum cultivars, with 20 varieties inscribed in the last 10 years [51].These new varieties are more responsive to chemical inputs, resistant to diseases, and can reach average yields of 4-5 t ha^{-1} under rainfed conditions [52]. 'Utuba' was released in 2015 as an alternative variety to 'Mangudo' and 'Mukuye', because of its amber seeds, high protein content and high yield potential. The grain yield performance on research station ranged from 3.4 to 6.5 t ha^{-1} and from 2.5 to 4.5 t ha^{-1} in farmers' fields [53]. 'Utuba' takes 62 days to (head) and 108 days to mature, and it is also appreciated by its good height (82 cm), which ensures good amount of straw for the livestock. A survey conducted by ICARDA has indicated that farmers that abandon the widely-grown durum cultivar 'Ude' (Chen/Altar//Jori69) to cultivate the recent release 'Utuba' (Omruf1/Stojocri2/3/1718/BeadWheat24//Karim) (**Table 2**), obtain an average yield gain of 82% and an equivalent monetary return. Regardless of this clear advantage, adoption by farmers remains very low [54], mainly because of the high cost of purchasing quality seeds, scarce access to agriculture micro-credits, and a national seed system incapable of also reaching the more remote areas [55]. To resolve some of these issues, international agricultural research centers and development agencies together with the national agricultural research institutes have launched a project to develop informal "Community Based Seed Enterprises" [56-59]. This informal system promotes farmers aggregation around the possibility to gain access to improved seeds from their neighbors. Lead farmers are designated and provided free-of-charge with certified seeds of improved varieties. These leaders are then responsible for multiplying the seeds and providing them to their neighbors for a reasonable price agreed among each other, often involving exchange of livestock, land rental, or payments after harvest. A significant effort has been made to expand the production of improved durum wheat cultivars to supply raw materials to the food

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industries. For example, in 2018-19 cropping season, Bale Zone Bureau of Agriculture scaled out two durum wheat cultivars (cvs. Utuba and Mangudo) in nine districts covering over 6.244 ha. In north Shoa-Amhara region, Africa RISING project in partnership with North Shoa Zone Bureau of Agriculture scaled out the two cultivars on over 700 ha In 2017-18 season this variety released in 2015 was reported to be cultivated on over 1,000 ha, which become 10,000 ha the following season, proving its fast adoption pace due to the national and international effort of promoting it, and the farmers appreciation of it. Further, the recent contractual agreement between Minjar farmers and ALVIMA pasta processing factory is predicted to provide an additional push to its adoption.

Until today, Ethiopia still cultivates emmer wheat, the ancestor of durum wheat. Its cultivation is mainly restricted to marginal areas by about 300,000 households, covering 36,000 ha with an average productivity of 1.7 t ha^{-1} as recorded during the 2013–2014 season [60-61]. This area also continues to be drastically reduced due to expansion of modern bread wheat cultivars. Improvement of emmer wheat is given little attention and only two cultivars ('Sinana-1' and 'Lemesso') have been released through selection from landraces [51]. This crop is mainly used for the preparation of local food products, such as *defo* or *dabo* (bread), *injera* (flat pancake bread), porridge, *kita* (flat steamed bread), *Kinche* (boiled coarse grain) and local drinks [62]. Emmer wheat is recommended for mothers as a special diet to maintaining their health and strength after childbirth because of its high protein content and digestibility [64]. In fact, its grain protein content ranges from 8.5 to 21.5%, which is 5–35% higher than in grain from oats or barley, and it has a very low glycemic index [63]. Emmer wheat is also a good source of

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resistance to leaf and stem rusts, powdery mildew, *Septoria* glume blotch, *Fusarium* head blight, Russian Wheat Aphid, in order of importance, and tolerance to drought and heat [65-69].

4. Durum wheat value chain in Oromia region, Ethiopia

At present, investments in pasta making are extremely promising in Ethiopia to intercept the new food habits of the growing urban populations, which are looking for fast, and tasty foods, while still cheap, diversified and nutritious. Pasta represented such a ready-to-use option since its first introduction in Ethiopia in 1938 by the pioneering Italian enterprise Colonalpi (currently called Kaliti Food Share Company), later followed by the establishment of state-owned industries for feeding the growing nation. Today the state industries have been privatized and participate, together with numerous new ones in the Ethiopian Millers Association. These pasta producers used to rely on massive importation of durum wheat grain, which was not a sustainable long-term business strategy due to its high costs and the competition for the use of available hard currency stocks with other national priorities. Indeed, the revamping of a national value chain has caused the reduction of durum wheat import to negligible amounts in 2015 [70] after having equaled € 129 million in 2013 (**Table 1**). However, at the same time, pasta import increased two-fold between 2011 and 2015, when it reached 50,000 t at a cost of about € 40 million [70]. To revert this trend, the Ethiopian Millers Association has eagerly explored the possibility to procure the needed raw material directly from local farmers in order to reduce production costs and increase competitiveness against foreign pasta imports. Unfortunately, the local production did not guarantee sufficient rheological grain quality to satisfy the industrial needs. In fact, grain of tetraploid landraces does not meet industrial standards in terms of color or protein quality, while the high-yielding modern varieties tend to produce bleached and “chalky” grains when

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grown on waterlogged vertisols in the absence of abundant nitrogen fertilization [71]. Hence, specific incentives needed to be provided to farmers to obtain industrial quality grain. The scope of the Ethiopian-Italian cooperation project of the Agricultural Value Chain in Oromia (AVCPO) was to re-direct some of the already existing bread wheat production system of the Bale zone toward the more lucrative farming of durum wheat for the industry. The process acted on the key elements required by the pasta industry to stabilize and self-sustain the value chain: competitive price, high rheological quality for conversion into pasta, easy and timely delivery, consistent stock of grains, and predictable increases over years (**Fig. 2**). Launched in April 2011, the initial steps relied on just two durum varieties (**Table 2**), identified as highly productive, resistant to prevailing diseases in the Bale zone, and with good gluten strength: 'Ejersa' (Labud/Nigris3//Gan) and 'Bakalcha' (980SN Gedirfa/Gwerou15). A total of 40 t of certified seed were purchased from the Sinana Agricultural Research Center (SARC). The dialogue with the pasta industries resulted in the signing of an innovative supply contract that set the purchase value to the prevailing bread wheat price, with the addition of a 'premium' strictly proportional to kernel protein content. This contract provided the needed incentive to farmers for the application of adequate fertilization strategies and has ensured high grain quality. Furthermore, to supply the industry with large and uniform stocks of grains, AVCPO promoted farmer aggregation into 15 cooperatives and four unions, and provided each with warehouses for temporary storage of grain. To measure the required quality, AVCPO equipped the SARC durum quality laboratory, and trained researchers and technicians. Small-holder farmers cultivating around 0.5 to 2 ha of land were able to deliver their small sales to the warehouses and from there the industry could purchase large bulked stocks, as needed. Technical assistance to farmers and

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304 needed continuous research efforts were delivered by regional research and development
305 institutions both from central and district-commune branches.
306
307 As highly innovative contractual relationships were created among farmer cooperatives and
308 industries, the surrounding authorities and public institutions were asked to provide support and
309 surveillance on proper accomplishment of duties. Among these, SARC formally acted as neutral
310 third party for measuring the protein content and determining the final price. The emphasis on
311 the highest level of participation and ownership by all involved stakeholders was considered as
312 the key element for the success and sustainability of the development process [72].
313
314 Since the first harvest, durum wheat provided to farmers a significant monetary gain per ha of 25
315 to 30% over concurrent bread wheat, and the industries were greatly satisfied with good
316 rheological quality and reduced prices over imports. The availability of seed stocks of the two
317 selected varieties enabled for prompt expansion of area planted through newly adopting farmers
318 and cooperatives. Over time, the self-sufficient nature of the AVCPO's complex of cooperatives
319 and institutions has created the premises for a vibrant market-oriented community eager to
320 absorb and valorize new varieties and technologies developed by their research partners.
321
322 Especially in the current situation of evolving rust races dramatically affecting bread wheat in the
323 Bale and other wheat belts, farmers attribute to durum wheat the role of a rescue crop. By the
324 convergence of all these factors, durum wheat production has exponentially increased from 500 t
325 in 2011-2012, to a record harvest of 4.6 million t in 2017 due mainly to the 'Utuba' recent
326 release and cultivation for large scale production. 'Utuba' was christened and released as

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Ethiopian durum wheat variety in 2015 [73]. In the meantime, the value chain is already expanding to nearby Arsi and Shewa zones (**Fig. 2**).

The example of Oromia can be considered a successful approach on integration of the whole durum wheat value chain [74]. It should be also considered for application in other SSA countries that rely today on durum wheat and pasta imports.

5. Durum wheat in West Africa as a future cash crop

West African countries cultivate over 7 million ha of irrigated rice, but only 100,000 ha of wheat (mainly bread wheat) and mostly in Nigeria. A recent steep increase of wheat area has been reported for Nigeria, but these data are not yet available from FAO statistics, the main source used for compiling **Table 1**. Still, all West African countries are importers of wheat grain and its derived products. A total of € 155 million worth of pasta and € 193 million worth of durum grains were imported in 2013 (**Table 1**). Benin is the largest importer of pasta in West Africa with almost € 51 million worth imported in 2013, followed by Niger, Burkina Faso, and Togo, which are also among the largest importers in Africa with € 20, € 22, and € 27 million worth, respectively. Interestingly, € 87 million worth of pasta are re-exported each year, mostly by Côte d' Ivoire and Nigeria. Since the national durum production is close to zero, it means that large quantities of durum wheat grain are imported internationally, converted by the local industry into pasta products, and then sold locally and to neighboring countries. Hence, as was the case for the Oromia region in Ethiopia, there is potential for national durum cultivation to support this strong local industry, while sharing the € 180 million worth per year of the current import market with the local growers. In Nigeria, initial steps have already been undertaken to identify suitable

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durum varieties at the Kadawa, Kano field station. Here, 12 candidate varieties from CIMMYT's breeding program were assessed over two seasons. Trials reveal that their grain yields may be above 6.2 t ha^{-1} in 100 days by the top performer 'Anser8' (Altar84/Alondra//Sula) under gravity irrigation [75].

Mauritania is the largest importer of durum grain in West Africa with over € 51 million spent every year. This country has one of the most challenging agro-environments in West Africa, with farming substantially restricted to the narrow band along the Senegal River; where rainfall of up to 600 mm per year and irrigation water from the river sustain crop production (Agriculture in Mauritania, 2009). The Senegal River basin has a potential of irrigating 135,000 ha [76], of which less than 20% are currently utilized. The main crops are rice, pearl millet and cowpea. Wheat cultivation along the river is estimated at 8,200 ha, of which approximately 2,000 ha are grown with durum wheat. The only cultivated durum variety is 'Karim' (syn: 'Yavaros79', Jori/Anhinga//Flamingo), a widely adapted +35 years old CIMMYT-derived variety. Wheat is cultivated during the winter season in rotation with rice and cowpea under gravity irrigation. The window for growing wheat is rather narrow to avoid interfering with the cultivation of the two seasons of rice. Sowing has to occur between the end of November and the middle of December. The harvest is just 80 to 100 days later in early March. Regardless of this short season, two recent projects carried on at the experimental stations of Daara and Kaedi (U-Forsk2013 and SARD-SC) have revealed that yields of 3 t ha^{-1} could be reached along the Senegal River Valley. In response to these results, three new durum wheat varieties ('Haby' [Mrb5/T.dico Aleppo Col//Cham1], 'Elwaha' [Oslks/5/Azn/4/BezHF/3/SD19539//Cham1/Gdr2] and 'Bezater' [Ossl1/Stj5/5/Bicrederaa1/4/BEZAIZSHF//SD19539/Waha/3/Stj/Mrb3/6/Stj3//Bcr/Lks4/3/Ter3])

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were released in 2016 (**Table 2**) and their seed multiplication has begun [77]. On the opposite shore of the river, the field station of Fanaye in Senegal obtained yields as high as 6 t ha^{-1}, when early planting towards the end of November was achieved. The irrigable agricultural land of Senegal is divided along three rivers, (in order of importance): Senegal, Faleme and Casamance, thus providing a total estimated irrigable land of 350,000 ha [78]. The Senegal River valley alone accounts for 240,000 ha of potential arable land [79], of which 110,000 ha are currently used for rice cultivation. Since last year small farmers started growing improved and heat tolerant durum wheat varieties in the fields currently farmed with rice during the fallow season in winter, and this could help to replace the € 46 million worth of annual durum import by the national pasta industry. Furthermore, if the total rice area was to be converted to durum wheat instead of the fallow period, then this would be sufficient to generate an overproduction of durum grains to be exported to neighboring countries for an interesting price. Just as the wheat-rice rotation system has been the cornerstone of India's food self-sufficiency with over 10 million ha still cultivated today [80], it can also become a new boost for the West African agriculture. In addition, the integration of a legume crop in the rotation with durum wheat and rice would be desirable to also increase long-term soil health and agro-ecosystem stability. In this regard, a suggestion is made to replace one rice season with cowpea, an excellent source of food and feed, with very high market value. The cropping model suggested would then become rice-durum wheat-cowpea. This expansion into considering a pulse such as cowpea as part of the durum wheat production system is, however, beyond the scope of this review and shall not be discussed further.

A third country relying on the Senegal River for irrigation is Mali, whose production is concentrated along this and the Niger River. The total irrigable land is estimated at 340,000 ha

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[81] with a potential to further expand. The vast majority of the land is utilized for the production of rice and maize during the warm months. Wheat is cultivated during winter on just 10,000 ha, of which a very small portion is durum wheat (**Table 1**). The old variety 'Biskri-Bouteille' (Biskri/Bouteille) is the only reported release for Mali [82]. It is likely that the breeding activities and import from neighboring countries have resulted in more modern releases, but no document could be located. Similarly to its neighbors, Mali imports large quantities of pasta (for € 14 million) and part of it is further exported (for € 0.2 million). Hence, local production of durum wheat is a viable option for all three countries along the Senegal River. Their total area currently cultivated with rice reaches 754,000 ha. Assuming the same conditions apply to the whole surface, cultivation of durum wheat during the short winter fallow season has the potential to generate additional food, without reducing the current production of the staple food. The newly identified super-early and heat tolerant durum varieties released in Mauritania and Senegal ('Haby', 'Elwaha', 'Bezater', and 'Amina': Korifla/AegSpeltoidesSyr//Loukos) can provide good industrial grain for the national industry and hold the potential to generate more than 1 million t of additional food in Sub-Saharan Africa [77].

The situation in Nigeria is no different than that observed for the Senegal River countries, even though, with over 80,000 ha farmed to wheat in 2013, it is already the largest bread wheat producer in West Africa (**Table 1**). A recent push by the Nigerian government, such as the removal of subsidies for the imported grains, has incentivized farmers to increase their wheat production, and MY2018/19 area harvested and production are estimated at 60,000 hectares and 60,000 tons, respectively.[83]. Wheat is typically planted in November or December and harvested around April. The land used for wheat production is then rotated for other rainfed

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crops during the rainy season, which lasts in northern Nigeria from April to September. Rice is sometimes grown after wheat. The amount of land occupied by durum wheat is not declared in any of the available documents. Certainly, Nigeria imports € 38 million per year of durum wheat grain to be converted into pasta for the national and export market (€ 41 million EUR worth). Hence, the local industry could certainly benefit from an increase in national production. Considering that the area cultivated with rice exceeds 2.9 million ha and that irrigation water is readily available in many parts of the countries, it certainly suggests a great potential for expansion, during the cool winter off-season.

Similarly, Guinea is a large importer of durum grain (for € 17 million EUR), but none is currently produced on the 1.6 million ha of rice cultivation. Côte d'Ivoire is the largest exporter of pasta (€ 32 million worth per year), but also one of the largest importers of durum grain (€ 28 million worth), with no production of wheat recorded on the 790,000 ha of rice cultivation (**Table 1**).

In summary, West African countries have the potential to convert offseason part of their 7.2 million ha of rice fields into durum wheat cultivation, instead of having an unproductive winter fallow . New, very early and heat tolerant varieties have been developed, tested, and confirmed along the Senegal River [77] and their seed is readily available through the CGIAR WHEAT. Their cultivation could turn an annual import market of € 185 million worth of grain and almost € 200 million worth of pasta into a national income to improve industrialization, create jobs, and reduce poverty in rural areas.

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6. Southern and Central Africa durum wheat use in the industry with limited cultivation

Southern and Central African countries cultivate 1.6 million ha of rice and 0.65 million ha of wheat. Unfortunately, data on wheat cultivation in Central Africa are few and unsubstantial. Among Southern African countries, durum wheat is cultivated on just 26,500 ha, mostly in South Africa and Zimbabwe. The most widely cultivated varieties are the 'Desert' durum developed in Arizona and California, with "Kronos" (Arizona Plant Breeders male sterile-facilitated recurrent selection population selection) as the preferred one (**Table 2**). All countries obtain yields above 4 t ha^{-1}, which only partially meets the national industry demand. Still, part of the grains is exported for generating an income of € 38 million.

All countries combined imported € 160 million worth of durum grain in 2013 (**Table 1**). The largest importers of grain were Malawi, South Africa, and Zimbabwe, which use it to sustain their national pasta industry. In fact, South Africa utilizes the grain to generate pasta for re-export with a value addition of over € 11 million, while Cameroon reaches € 1.4 million of pasta exports annually. Interestingly, some SSA countries do not apply import taxes on durum wheat, which in turn has promoted cases of illegal false labeling of bread wheat grain as durum wheat to avoid custom costs [84]. The import of pasta products in 2013 was € 108 million worth, and the biggest importers were South Africa and Madagascar, with € 31 and 26 million worth, respectively. Therefore a business opportunity exists for the local pasta industry, while creating the opportunity for growers to improve their livelihoods. Considering an average price per ton of durum wheat grain of € 300 on local markets, and attainable yields of 3 ton ha^{-1}, approximately 160,000 ha of the currently cultivated 650,000 ha of bread wheat would need to be converted to

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fill the production gap. Obviously, the reduction of bread wheat would in turn open a gap in the availability of national bread flour, pushing the country to further imports. However, import prices of bread wheat flour is significantly cheaper than durum wheat imports, especially when considering that durum wheat production is a trade that does not require government subsidies to be profitable. Hence, the national economy would overall benefit from a production shift toward durum wheat, as long as this does not upset the higher price paid for semolina. Furthermore, durum bread wheat flour blends are commonly used in North Africa for the baking of affordable and protein-rich breads.

A second consideration is in regard to the spread of diseases. In fact, South Africa has been monitoring a growing threat of Karnal Bunt disease [85], while Uganda is the first country where the devastating stem rust race Ug99 was observed, before it spread to the neighboring countries [86]. Both of these diseases affect prevalently bread wheat, while durum wheat has thus far remained resistant [87-88]. Hence, replacement of bread wheat by durum wheat would not only have a potential valuable effect on the economy, but also reduce the incidence of damaging diseases on the wheat crop. Alternatively, durum wheat could be cultivated on part of the 1.8 million ha dedicated to rice during the fallow off-season period, assuming that adequate rainfall or irrigation water is available. This could be the case for Madagascar, where durum wheat could be cultivated during the off-season in the same terrace fields grown with paddy rice [89]. In fact, a recent study on wheat suitability in SSA [44] using geospatial analysis revealed that Angola, Mozambique, Zambia, and Zimbabwe are the countries with the largest potential extension of suitable land for establishing wheat production. The suitable mega environments identified were

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highlands with high rainfall and frequent diseases (ME2A [90]), and drought prone rainfall with cold winter months (ME4A).

7. Durum wheat cultivation in the Saharan oases: a staple food of tradition

The Sahara oases are unique environments that remained impervious to modernization. In this review both types of oases are considered, those areas of desert where water surfaces from the soil or where it can be collected by human activities through dams (*barrage*) or other methods as defined by Zaharieva et al. [91]. Semi-nomadic tribes live in these locations and developed self-sustaining agricultural systems based on the sporadic rainfalls and underground or aboveground water accumulations. Several major oases can be found in SSA in Chad, Mali, Mauritania, Niger, and Sudan, but also in Algeria, Egypt, Libya, Morocco, and Tunisia. There are no extensive records of the total area cultivated. The Saharan oases are estimated at a total surface of 900,000 ha, of which approximately half is used for intensive agriculture [91]. Further, average sizes for oases are between 5 and 200 ha of cultivated land, depending on the abundance of yearly rainfall or available percolated water, and can sustain the life of up to 1,000 people per oasis [92]. In Mauritania, 350 oases account for a total surface of cultivation by wheat (bread and durum) of over 2,000 ha [93]. Roughly the same area is cultivated in the oases of Mali [94], while the five largest oases in Algeria (Ghardaia region) account for 2,200 ha of cereal culture [95], and in Morocco the major oasis region of Errachidia cultivates an approximate 5,000 ha of cereals [96]. Cultivated crops include sorghum and millet as rainfed crops, both types of wheat and cowpea as irrigated crops. Larger oases have access to a constant water supply, allowing irrigation by pivot or drip irrigation, such as in the regions of east of Morocco and Algeria [97]. In these cases, water is pumped as needed, and wheat is often cultivated among date palms with the moisture

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used by both cultures. In most other cases, large quantities of water are available only during specific times of the year, and to collect it in sufficient amounts for cultivation, it is necessary to build temporary dams with clay, sand, and stones. The dam is then opened at the beginning of the winter and as the water recedes, holes are dug into the mud and cereal grains are placed inside (**Fig 3**). Growing on residual moisture and with high temperatures, the yields rarely exceed 0.5 t ha^{-1}, while under pumped irrigation yields of 4 to 5 t ha^{-1} are common [98].

The farmers of the desert cultivate mostly wheat biotypes of unique morphology defined as *oasiensis* types, which represent mixtures of several tetraploid and hexaploid wheat species (for review see: [99]). Durum wheat cultivation in the oases dates to the initial trade routes between the Nile Valley and West Africa [91]. Several traditional dishes are made from this crop, and its straw is very important as feed for the small ruminants and camels. The 'Alkama Binka' type is one of the durum wheats most frequently found [82], but also the 'Amekkaoui' and 'Cheguira' types are found in the Saharan oases of Algeria and Morocco, respectively [100]. Modern cultivars have also been introduced such as 'Waha' (syn. 'Cham1', Plc/Ruff//Gta/Rtte) in Algeria and 'Karim' in Mauritania, and their superior yields are causing a contraction in the use of landraces (**Table 2**). The wealth of genetic diversity of germplasm from the Saharan oases has been recognized by several authors and several calls for better collection and conservation have been made, but with limited success [99]. In consideration of the harsh environment where these landraces thrive and the fact that durum production will be greatly stressed due to climate issues in the Mediterranean basin [101], they certainly represent a valuable resource of useful alleles for heat, drought, and salinity tolerance, which can be deployed in breeding for climate change adaptation. Furthermore, the oases represent fragile ecosystems, where land availability is dependent on rainfall and maximum yields per unit of land are more critical than anywhere else.

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In that sense, the introduction of modern agronomy and irrigation practices, in integration with targeted breeding efforts could deliver true game changers. Alternatively, the reduced available land surface could be used as an advantage to generate very exclusive durum products. In fact, the 'rarity' could be exploited through well integrated value chains to deliver products at elevated prices on the occidental markets, as is already the case for the oases dates. Considering that oases produce less than 5% of their needs in cereals [95], and the rest is purchased from neighboring towns, the possibility of generating larger incomes would be a suitable strategy to tackle famine. In that sense, the already high value of durum grains could be further exploited via smart-marketing to increase the revenues.

8. Future prospects: a south-south collaboration to expand durum wheat cultivation in Africa

All of Africa accounts for an annual import of € 4.1 billion worth of durum grain to supply the national pasta and couscous market. These are mostly imported to North Africa (NA) from Canada, USA, and Turkey (**Table 1**). North Africa already cultivates durum wheat on 2.9 million ha, and the area for further expansion is limited. This opens an opportunity for SSA to gain access to an € 3.7 billion annual market by filling part of the grain needs of NA. The current area dedicated to wheat cultivation in SSA is limited to 2.6 million ha, mostly in Ethiopia, South Africa and Sudan. In Ethiopia, new interest has sprung toward the promotion of industrial crops such as durum wheat to provide the local manufacturers with prime raw material without the need of relying on expensive imports. In addition, urbanization has shifted the food habits of many countries, and pasta has gained steadily in appreciation by African consumers. Furthermore, the case presented for cultivation of durum wheat in rotation with rice along the

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Senegal River, matches what is already customary on over 10 million ha of wheat-rice or wheat-rice-rice rotations in India [80]. In that sense, there is large potential for wheat expansion on the 9.1 million ha of rice land in SSA. Since further expansion of the wheat areas will require additional investments and will face the risk of reduced yields, it appears logical to seek the wheat type that would provide the maximum monetary return for unit of land converted. Durum wheat in this case would represent an ideal cash crop to help reduce poverty in SSA. For comparison, the average import prices of major cereals to South Africa [102] for the year 2015 were at: US$ 502 t^{-1} aromatic rice, US$ 330 t^{-1} durum wheat, US$ 278 t^{-1} malt barley, US$ 209 t^{-1} hard red bread wheat, US$ 171 t^{-1} sorghum and US$ 150 t^{-1} feed maize. While it is true that import prices change for each country based on access to trade, existence of infrastructure, and specific import policies, South Africa provides a good example of a reactive trading nation in SSA. On this basis, it is evident that durum wheat remains one of the most income advantageous winter cereals, significantly more expensive than bread wheat and malt barley. However, to succeed in the utilization of the financial return of this crop, it is necessary to have a well-integrated value chain capable of delivering profitable economic returns to farmers. The example of the durum wheat value chain in the Oromia region of Ethiopia could be repeated in several other regions and should provide a good guideline to be out-scaled to other countries. Still, the industrial machinery and the strategy for production need to be harmonized among African countries to generate a fair and vibrant market. The desire for semolina-based food is expected to increase in the years to come [103], but the national industry will be successful in targeting the demand only if their products can compete not just in price, but also in quality with the imported ones. In that sense, great traditional and modern knowledge for cultivation and production of this crop exist already in North Africa and Ethiopia. Breeding programs for this crop have been

successful in targeting the harsh drought conditions of North Africa and the disease pressure in Ethiopia. In order to expand the production of this crop to non-traditional territories, the expertise gathered there could be transferred to SSA in the form of novel and adapted varieties. It is therefore desirable that Ethiopian breeders could produce varieties well adapted to the SSA mega-environment of type 2A, with high rainfall and high disease pressure. Instead, Egyptian breeders could help in delivering varieties targeted to the hot and irrigated areas of mega-environment type ME1, such as West Africa and Sudan. The other North African countries could target ME4A, with low rainfall and cold winters, as well as help in the further development of the Saharan oases. Altogether, this envisioned South-South collaboration could ensure that varieties developed in traditional durum growing areas such as North Africa and Ethiopia, would adapt to the conditions of the southern partners. Harvests could then be sold to those African countries with strong pasta industries, and the finished semolina products would be sold all over Africa. This integrated value chain would ensure a steep increase in monetary circulation and an overall reduction in the poverty of Africa. Recent publicly funded projects like Africa Rising (www.africa-rising.net), SARD-SC (www.sard-sc.org), TAAT (www.iita.org/taat), and U-Forsk2018 have targeted the increase in production of wheat in SSA, and created the basis to hope for a comprehensive "durum wheat revolution" in SSA.

Acknowledgments: We would like to thank the Swedish Research Council (Vetenskapsrådet) who funded the research along Senegal River through the projects U-forsk 2013–2017 "Deployment of molecular durum breeding to the Senegal basin: capacity building to face global warming" and U-forsk 2018–2021 "Genomic prediction for breeding durum wheat along the Senegal River Basin".

602

603 **Author Contributions:** All authors participated in collecting data and writing this review.

604 **Conflicts of Interest:** The authors declare no conflict of interest. The founding sponsors had no

605 role in the writing of the manuscript, and in the decision to publish the results

606

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912 **Table 1. Economy and production of durum wheat in sub-Saharan Africa**

	Crop use per land			Durum exports[b]		Durum imports[b]	
Country	Rice[a]	Wheat (all)[a]	Durum	Grains	Pasta	Grains	Pasta
	(ha)	(ha)	(ha)	(€)	(€)	(€)	(€)
Eastern	74,069	1,931,714	599,552	365,889	247,159	129,119,247	46,339,452
Eritrea	-	25,000	12,500[c]	-	-	-	8,210,000
Ethiopia	33,820	1,605,654	561,979[d]	-	28,079	129,113,334[q]	24,433,488[q]
Kenya	31,349	162,900	16,290[e]	365,889	219,080	2,177	13,695,964
Somalia	1,338	2,500	na	-	-	3,735	-
Sudan	7,562	135,660	6,783[f]	-	-	na	na
Central	206,592	44,687			1,636,218	11,864,150	21,908,766
Burundi	21,670	8,828	na	-	1,324	3,136	226,183
Cameroon	166,734	660	na	-	1,487,086	11,858,665[q]	13,442,925[q]
Gabon	620	-	-	-	69,532	2,349	5,665,685
Rwanda	17,568	35,199	na	-	78,276	-	2,573,974
Southern	1,437,257	608,622	26,521	38,590,262	11,794,879	148,416,094	86,270,994
Angola	29,510	3,420	720[g]	-	-	1,229	-
Madagascar	909,492	2,087	na	-	2,730	142,521	26,445,917
Malawi	65,275	1,269	na	-	3,862	34,292,325[q]	808,085
Mozambique	300,000	18,081	-	1,295	-	-	3,568,930
South Africa	1,150	505,500	23,456[h]	35,183,511	11,702,825	33,889,190	31,108,885
Uganda[l]	93,000	14,000	100[i]	86,843	76,540	3,673,000	3,935,998
Zambia	38,520	41,810	0[l]	3,318,613	2,177	-	5,982,422
Zimbabwe	310	22,455	2,246[m]	-	6,745	76,417,829	14,420,757
West	7,394,599	102,033	4,302	1,123,513	87,653,612	193,535,341	155,068,054
Benin	68,259	-		474,234	222,295	8,365,599[q]	50,781,356[q]
Burkina Faso	138,852	-	-	-	65,747	272,228	22,915,826[q]
Gambia	66,380	-	-	-	536,030	-	5,094,377
Ghana	215,905	-	-	2,340	3,633,396	78,376	7,847,000[r]
Guinea	1,642,687	-	-	-	111,862	17,673,754	3,780,845
Ivory Coast	791,691	-	-	646,939	32,545,382	28,513,879[r]	3,024,576[r]
Mali	604,745	9,947	1,100[n]	-	211,989	-	16,050,025
Mauritania	43,900	1,700	na[0]	-	19,077	51,161,839	14,377,271
Niger	21,572	1,883	na	-	7,328,976	3,101,758	20,659,562[q]
Nigeria	2,931,400	80,000	na	-	40,917,371	38,300,083[q]	2,633,648
Senegal	108,547	3	2[p]	-	2,061,487	46,058,643[q]	7,903,568
Sierra Leone	671,422	-	-	-	-	9,182	-
Togo	92,239	-	-	-	2,099,984	-	27,284,750[q]
Africa	9,714,796	9,960,981	3,557,740	40,346,664	215,258,164	4,166,972,506	375,508,531
sub-Saharan Africa	9,112,517	2,687,056	632,375	40,079,663	101,331,868	482,934,832	309,587,266

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914 [1] The former Sudan is not a true Sub-Saharan country but it has agro-environmental conditions
915 that differ from North Africa and therefore it is presented here. Data consider Sudan and South
916 Sudan together.
917 [2] Uganda is reported among Southern Africa countries instead of East Africa for its closer
918 similarity in the use of durum wheat
919 [a] Data obtained from FAOSTAT of the 2013 season [104].
920 [b] Data obtained from The Economic Complexity Observatory of the year 2013 [15], except when
921 otherwise indicated.
922 [c] [105].
923 [d] [106].
924 [e] https://softkenya.com/farming/wheat-in-kenya/
925 [f] [107].
926 [g] [108].
927 [h] [44].
928 [i] [109].
929 [l] [84].
930 [n] [110].
931 [o] [104].
932 [p] Land surface utilized on-station.
933 [q] Data confirmed on Fact-Fish (www.factfish.com).
934 [r] Data confirmed on Index Mundi (www.indexmundi.com).
935

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936 **Table 2. Durum wheat varieties currently cultivated in Sub-Saharan Africa**

Country	Variety name	Adoption	Pedigree	Origin
Ethiopia	'Cocorit71'	Old variety, still cultivated	Enano/4*Tehuacan60//Stewart63/3/Anhinga	CIMMYT
Ethiopia	'Langdon(LD)357'	Old variety, still cultivated	LD308/Nugget	USA
Ethiopia	'Gerardo'	Old variety, still cultivated	GerardoVZ466/3/ND61130/Leeds//Grulla	CIMMYT
Ethiopia	'Ejersa'	Variety utilized by farmers in Oromia	Labud/Nigris3//Gan	CIMMYT
Ethiopia	'Bakalcha'	Widely cultivated variety, now replaced due to susceptibility to stem rust	Gedirfa/Gwerou15	CIMMYT
Ethiopia	'Ude'	Variety that replaced Bakalcha in most zones	Chen/Altar//Jori69	CIMMYT
Ethiopia	'Mangudo'	Covers several districts in Oromia	Omruf1/Stojocri2/3/1718/BeadWheat24//Karim	ICARDA
Ethiopia	'Asasa'	Low moisture area in Rift Valley	Cho/Taurus//Yav/3/Fg/4/Cra/5/Fg/Dom/6/Hui	national
Ethiopia	'Utuba'	New favorite by farmers, cultivated already on 10,000 ha	Omruf1/Stojocri2/3/1718/BeadWheat24//Karim	ICARDA
Ethiopia	'Sinana1'	18,000 ha	Emmer selection from landraces	national
Ethiopia	'Lemesso'	18,000 ha	Emmer selection from landraces	national
Mauritania	'Karim'	Cultivated by farmers along the Senegal river and in oasis	Jori/Anhinga//Flamingo	CIMMYT
Mauritania, Senegal	'Haby'	New release under fats-track multiplication	Mrb5/T.dico Aleppo Col//Cham1	ICARDA
Mauritania, Senegal	'Elwaha'	New release under fats-track multiplication	Oslks/5/Azn/4/BezHF/3/SD19539//Cham1/Gdr2	ICARDA
Mauritania, Senegal	'Bani Suef 5'	New release under fats-track multiplication	Dipperz/Bushen3	CIMMYT
Senegal	'Amina'	New release under fats-track multiplication	Korifla/AegSpeltoidesSyr//Loukos	ICARDA
Mali	'Biskri-Bouteille'	Old variety, still cultivated. Only available recorded release	Biskri/Bouteille	national
South Africa	'Kronos'	Most cultivated variety	APB MSFRS pop selection	USA
Kenya	'Mwewe'	Old variety, still cultivated	Flamingo/Leads	CIMMYT
Sudan	'Sham1'	Old variety, still cultivated	Plc/Ruff//Gta/Rtte	CIMMYT, ICARDA
Eritrea	'Mindum XA10'	Old variety, still cultivated	Mindum/Asmara10	USA
Nigeria	'Anser8'	Holds potential for adoption	Altar84/Alondra//Sula	CIMMYT

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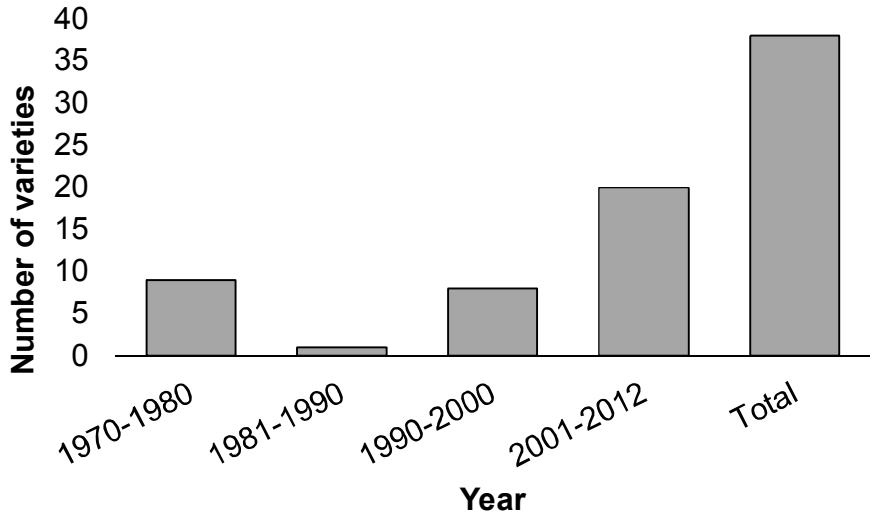

938

939 **Figure 1.** Durum variety releases in Ethiopia since 1970- 2012

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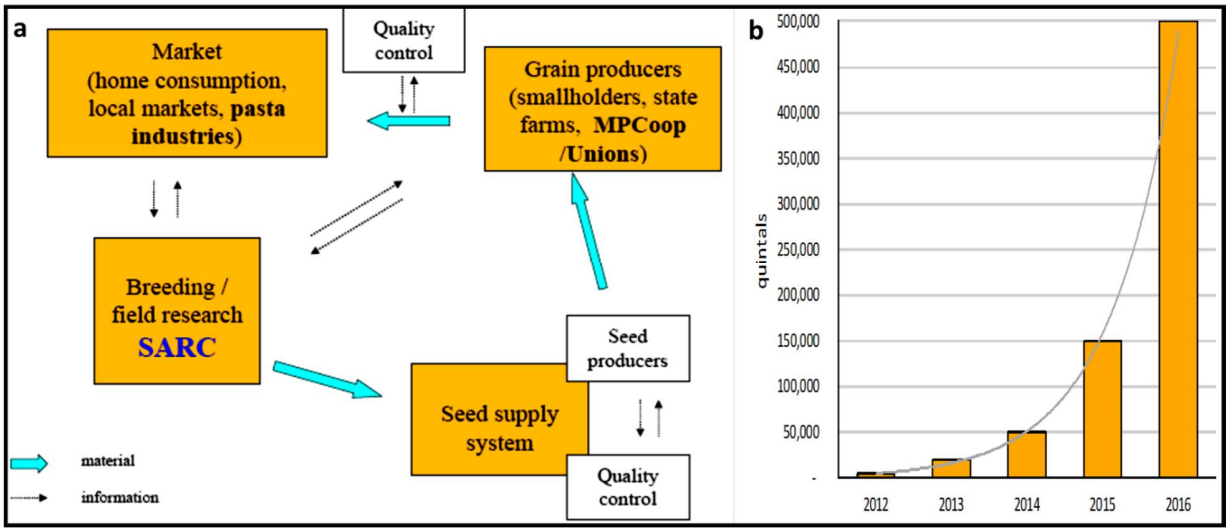

943

944 **Figure 2.** Durum wheat value chain in Oromia, Ethiopia. **a**. Schematic of the intervention and
945 value chain key actor relationships ; **b**. Success indicator measured as the amount of durum grain
946 sold in Oromia region since the inception of the project. SARC refers to the Sinana Agricultural
947 Research Center

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Figure 3. Wheat culitvation in oasis in Marutiania. *Left*- holes in the mud for the planting of durum wheat as the water retreats. *Right*- Gradient on plant maturity caused by the difference in planting time following the retreat of the water.