Assessing Technological Change in Agri-Food Systems of the Global South: A Review of Adoption-impact Studies in Wheat

Supplementary Materials

Supplementary Text.

Major Research-and-Development Interventions in Wheat Agri-food Systems of the Global South

The development and release of improved and high yielding varieties that are resistant to diseases and pests are widely considered as the significant research-and-development (R&D) interventions in response to the critical challenges faced in global food production (Gollin et al., 2018). The existing studies on the impact of wheat breeding research in the developing countries have shown a prominent role of CGIAR Centers, which continue to produce high rates of return (Heisey et al., 2003; Lantican et al., 2016). While there has been no slowdown in the rate of release of disease resistant, drought tolerant, biofortified and yield-enhancing varieties (Aktar-Uz-Zaman et al., 2017), a large portion of wheat area in many developing countries is still cultivated with landraces and older improved varieties (Atlin et al., 2017; Krishna et al., 2016; Yigezu et al., 2019b). The slow varietal turnover has shown to lower system productivity and enhance vulnerability to pests and diseases (Atlin et al., 2017). The slowdown of public and private investments in agricultural extension has worsened the situation (Pan et al., 2018). However, in many cases, the varietal traits that are preferred by farmers (who are also consumers) could not be delivered by new, improved varieties (e.g., taste), resulting in persistence of old improved varieties and landraces (Dalton, 2004; Weltzien and Rattunde, 2020). Against the backdrop of high demand heterogeneity and dynamic nature of production challenges faced by wheat farmers, one of the significant global challenges for the R&D actors is transferring the relevant germplasm and the associated information quickly into the hands of the world's poor, such as those living in South Asia and sub-Saharan Africa.

Another major area of CGIAR intervention with National Agricultural Research Systems (NARS) is 'sustainable intensification.' Under this umbrella term, several improved agronomic practices are developed and disseminated alongside improved varieties to produce more output while using potentially fewer resources on existing agricultural land and reducing adverse environment or ecosystem impacts (Pretty and Bharucha, 2014). The adoption of improved crop varieties and the creation of enabling environment through better market institutions are two essential components of sustainable agricultural systems. Still central to this concept is several improved agronomic practices that reduce production costs (Giller et al., 2015; Kotu et al., 2017). Zero-tillage with residue retention for soil cover is one such technology found to generate considerable agronomic and economic benefits while improving the environmental footprint of the production systems (El-Shater et al., 2016; Keil et al., 2017; Krishna and Veettil, 2014).

Developing micronutrient-enriched wheat through a combination of breeding and agronomic practices has been gaining importance in recent years. Foliar application of micro-nutrients, for example, has shown significant welfare implications for increasing not only crop yield but also the micronutrient content in the grains (Ram et al., 2015). Consumption of zinc-enriched wheat is supposed to ameliorate the lack of this nutrient in the food, which imposes a severe economic burden among the poor in the global South (Ram et al., 2016). Another critical intervention is system diversification with crops like millets and legumes, which would enhance not only system productivity but also the nutritional status of subsistence farm-households in rural areas (Birthal et al., 2015; Hossain et al., 2016). Despite their relevance, these technologies have so far received less research focus on adoption and impact studies. However, the scenario may change shortly with increased R&D attention to the quality of diets and its impacts on human welfare and planetary health (Willett et al., 2019). There is also mounting evidence on the detrimental effects of the heat and drought stress on the nutritional quality of wheat, especially lowering the concentrations of zinc and iron (Guzmán et al., 2016; Myers et al., 2014; Velu et al., 2016). These trends may necessitate new technological interventions shortly and would also shape the socioeconomic research on technology changes and wheat value chains.

Integrated management of crop pests including insects and weeds (Hassanali et al., 2008; Landis et al., 2016) and reduction of harvest and post-harvest losses (Khader et al., 2019; Tefera et al., 2011) are also other components of sustainable intensification that are gaining momentum, especially in the face of climate change and rapidly growing world population. Sustainable intensification can be a reality only when improved crop varieties along with the associated optimal agronomic management practices and better and enabling institutional, policy and market environments are in place (Pretty et al., 2018; Pretty and Bharucha, 2014).

The technological interventions in agriculture are often evaluated against the R&D investments to show how they led to desirable economic, social and environmental outcomes (Hurley et al., 2014; Pardey et al., 2016). In general, most of these studies have shown significantly high returns of R&D investments (Alston et al., 2012; Renkow and Byerlee, 2010). The CGIAR-related varieties are estimated to be cultivated in 64% of the wheat area in the developing countries (Lantican et al., 2016). The adoption of CGIAR varieties has resulted in a substantial increase in yields, improved grain quality, reduced yield variability, and improved tolerance to biotic and abiotic stresses (Byerlee and Dubin, 2010). Some researchers have observed that the distribution of impacts from agricultural R&D, in general, is highly skewed, and the high rates of return calculated for individual cases of success are unlikely to be representative of the overall portfolios (Maredia and Raitzer, 2010). Furthermore, aggregate rates of return in monetary terms are less useful while reporting on the attainment of desirable livelihoods and ecological impacts, including reduced poverty, improved food and nutrition security, improved natural resource and ecosystem services (Stevenson et al., 2018). Given that benefits from individual investments vary widely, targeting of investments is also required to generate the most exceptional livelihood and/or environmental impacts.

Only a few studies have addressed the environmental, poverty, and health impacts of R&D investments in wheat (Maredia and Raitzer, 2010). Nalley et al. (2010) examined the reduction in wheat yield variability due to CIMMYT-bred cultivars in the Yaqui Valley of Mexico. Marasas et al. (2003) showed the economic impact of the rust resistance by the wheat breeding program of CIMMYT. Gollin et al. (2018a) examined the impacts of Green Revolution technologies on national income of 84 countries during the 1960-2000 period. Available data have likely limited extending macro-impact studies to these broader dimensions. Sustainable intensification has also received relatively less attention in the field of macro-economic impact assessments (Renkow and Byerlee, 2010). While several location-specific and system-specific studies have quantified the yield advantages due to germplasm improvements, few have addressed the aggregate impacts of R&D on agronomic practices, management techniques, and, more importantly, technology packages combining improved varieties and optimal agronomic and management practices. Technology-driven intensification is also land-saving with the potential to arrest deforestation if accompanied by more robust regulatory frameworks (Byerlee et al., 2014; Stevenson et al., 2013).

Supplementary Table S1. Technology adoption studies in wheat production systems (2008-2017)

(Study)	Country	Technology	Data sources	Data type	Analytical tool	Remarks
(Ali and Erenstein, 2017)	Pakistan	climate change adaptation practices	farm survey (n =950)	cross-sectional	probit, censored least absolute deviation	determinants of use and number of practices used.
(Abay et al., 2017)	Ethiopia	chemical fertilizers, improved seeds, and irrigation	farm survey (n =7500)	longitudinal	multivariate probit	implication of farmers' locus of control on their technology adoption decisions
(Keil et al., 2017)	India	conservation tillage	farm survey (n = 990)	cross-sectional	probit with sample selection	determinants of adoption correcting non-exposure bias.
(Rahut and Ali, 2017)	Pakistan	climate-risk mitigating strategies	farm survey (n =500)	cross-sectional	multivariate probit	determinants of choice of adaptation strategies by farmers
(Joshi et al., 2017)	Nepal	climate-risk adaptation	farm survey (n =120)	cross-sectional	logit	determinants of climate change adaptation technologies and practices
(Mottaleb et al., 2016)	Bangladesh	scale-appropriate machinery	agricultural census (n = 25.35 million) and sub-sample (n = 1.16 million)	cross-sectional	multinomial probit	determinants of ownership of machineries.
(Singh et al., 2016)	India	zero tillage	farm survey (n =40)	cross-sectional	logit	determinants and reasons for adoption
(Ali et al., 2016)	Pakistan	irrigation	farm survey (n = 950)	cross-sectional	multivariate probit	determinants of farmers' choice of water pumps.
(Kumar et al., 2016)	India	zero tillage	farm survey (n =240)	cross-sectional	descriptive	knowledge, attitude, and perception toward technology
(Keil et al., 2016)	India	conservation tillage	survey among service providers (n = 277) and farmers (n = 991)	cross-sectional	Heckman selection	determinants and profitability of conservation tillage service provision.
(Nazli and Smale, 2016)	Pakistan	new varieties	farm survey (n =1116)	time-series	duration model	demand for varietal traits; farmer heterogeneity.

(Study)	Country	Technology	Data sources	Data type	Analytical tool	Remarks
(Teshome et al., 2016a)	Ethiopia	soil and water conservation	farm survey (n =272)	cross-sectional	ordered probit	adoption phases
(Meena et al., 2016)	India	zero tillage	farm survey (n =180)	cross-sectional	multinomial logit	reasons for non- and dis-adoption and constraints in adoption
(Krishna et al., 2016)	India	new varieties	secondary data from public seed sector	time series	descriptive	trend in demand for breeder seeds and production.
			farm survey (n =323)	cross-sectional	ordinary least squares	determinants of varietal turnover in farmers' field.
(Teshome et al., 2016b)	Ethiopia	sustainable land management	farm survey (n =300)	cross-sectional	multivariate probit	role of farmer perceptions on investment
(Ali et al., 2015)	Pakistan	certified seeds	farm survey (n =367)	cross-sectional	binary variable (not specified)	adoption modelling as a preliminary step for impact assessment
(Mahmood et al., 2015)	Pakistan	water-saving technologies	farm survey (n =270)	cross-sectional	none	adoption level of water-saving irrigation interventions
(Magnan et al., 2015)	India	laser land leveling	randomized control trial (n = 478)	experimental	ordinary least squares	role of heterogeneous information on adoption.
(Shiferaw et al., 2014)	Ethiopia	improved varieties	farm survey (n = 2017)	cross-sectional	probit	determinants and impacts of farmer adoption of improved varieties.
(Singh et al., 2012)	Bangladesh, India, Nepal, Pakistan	resource-conserving technologies	village survey (n = 56)	cross-sectional	descriptive	extent of exposure and adoption of technologies
(Kassie et al., 2011)	Ethiopia	soil conservation	farm survey (n=148)	cross-sectional	logit	adoption modelling as a preliminary step for impact assessment
(Erenstein, 2010a)	India, Pakistan	conservation tillage	secondary data, supply-side surveys (n = 78), farm surveys (n = 858)	cross-sectional	descriptive	presents a triangulation approach to assess technology diffusion.

(Study)	Country	Technology	Data sources	Data type	Analytical tool	Remarks
(Erenstein, 2010b)	India	conservation tillage	village survey (n = 170)	case-studies	descriptive	village surveys to explore technology dynamics.
(Matuschke and Qaim, 2009)	India	new varieties	farm survey (n =282)	cross-sectional	Tobit, probit	effect of social networks on adoption
(Erenstein and Farooq, 2009)	India, Pakistan	conservation tillage	farm survey (n = 527)	cross-sectional	bivariate analysis	determinants of adoption and dis-adoption .
(Kassie et al., 2009)	Ethiopia	conservation tillage, compost and chemical fertilizers	farm survey (n = 130) and plot-level data (n = 348)	cross-sectional	trivariate probit	estimated inter-dependence adoption of 3 practices.
(Singh et al., 2008)	India	zero tillage	farm survey (n =100)	cross-sectional	descriptive	knowledge, attitude, and perception toward technology
(Torkamani and Shajari, 2008)	Iran	Irrigation	farm survey (n =187)	cross-sectional	probit	relative risk premiums to estimate adoption model

Supplementary Table S2. Technology impact studies in wheat production systems (2008-2017)

(Study)	Country	Technology	Data sources	Data type	Method to address the selection bias	Key output/outcome variable(s)
(Ali and Erenstein, 2017)	Pakistan	climate change adaptation practices	farm survey (n =950)	cross-sectional	matching	food security, poverty
(Abro et al., 2017)	Ethiopia	rust-resistant varieties	farm survey (n =2069)	2-year panel	panel data (fixed effects)	Yield
(Ali et al., 2017)	Pakistan	Irrigation	farm survey (n =917)	cross-sectional	matching	yield, income, poverty, land rent, water scarcity
(Rahut and Ali, 2017)	Pakistan	climate-risk mitigating strategies	farm survey (n =500)	cross-sectional	matching	yield, income, poverty
(Kathpalia and Chander, 2017)	India	agricultural machinery	farm survey (n =100)	cross-sectional	none	NA (simple tabulation of farmer perceptions)
(Singh, 2017)	India	resource-conserving technologies	farm survey (n =240)	cross-sectional	none	yield, net income
(Singh et al., 2016)	India	zero tillage	farm survey (n =40)	cross-sectional	none	yield, net income
(Khatri-Chhetri et al., 2016)	India	climate change adaptation practices	farm survey (n = 1267)	cross-sectional	none	input costs, grain yield
(El-Shater et al., 2016)	Syria	zero tillage	farm survey (n=621)	cross-sectional	endogenous switching, matching	net returns and wheat consumption
(Rahut et al., 2016)	Pakistan	Irrigation	farm survey (n =950)	cross-sectional	matching	food security, income, poverty
(Aryal et al., 2016)	India	zero tillage	farm survey (n =208)	2-year panel	none	grain yield (under normal and excess rainfall)
(Keil et al., 2015)	India	zero tillage	farm survey (n =1444)	cross-sectional	none	grain yield
(Aravindakshan et al., 2015)	Bangladesh	conservation tillage	farm survey (n =328)	cross-sectional	none	energy use efficiency
(Aryal et al., 2015a)	India	laser leveling	farm survey (n =198)	cross-sectional	none	grain yield, irrigation time
(Aryal et al., 2015b)	India	zero tillage	farmers field trials (n = 40)	3-year panel	none	CO_2 emission, profits
(Krishna and Veettil, 2014)	India	zero tillage	farm survey (n =180)	cross-sectional	none	grain yield, cost of cultivation, technical efficiency

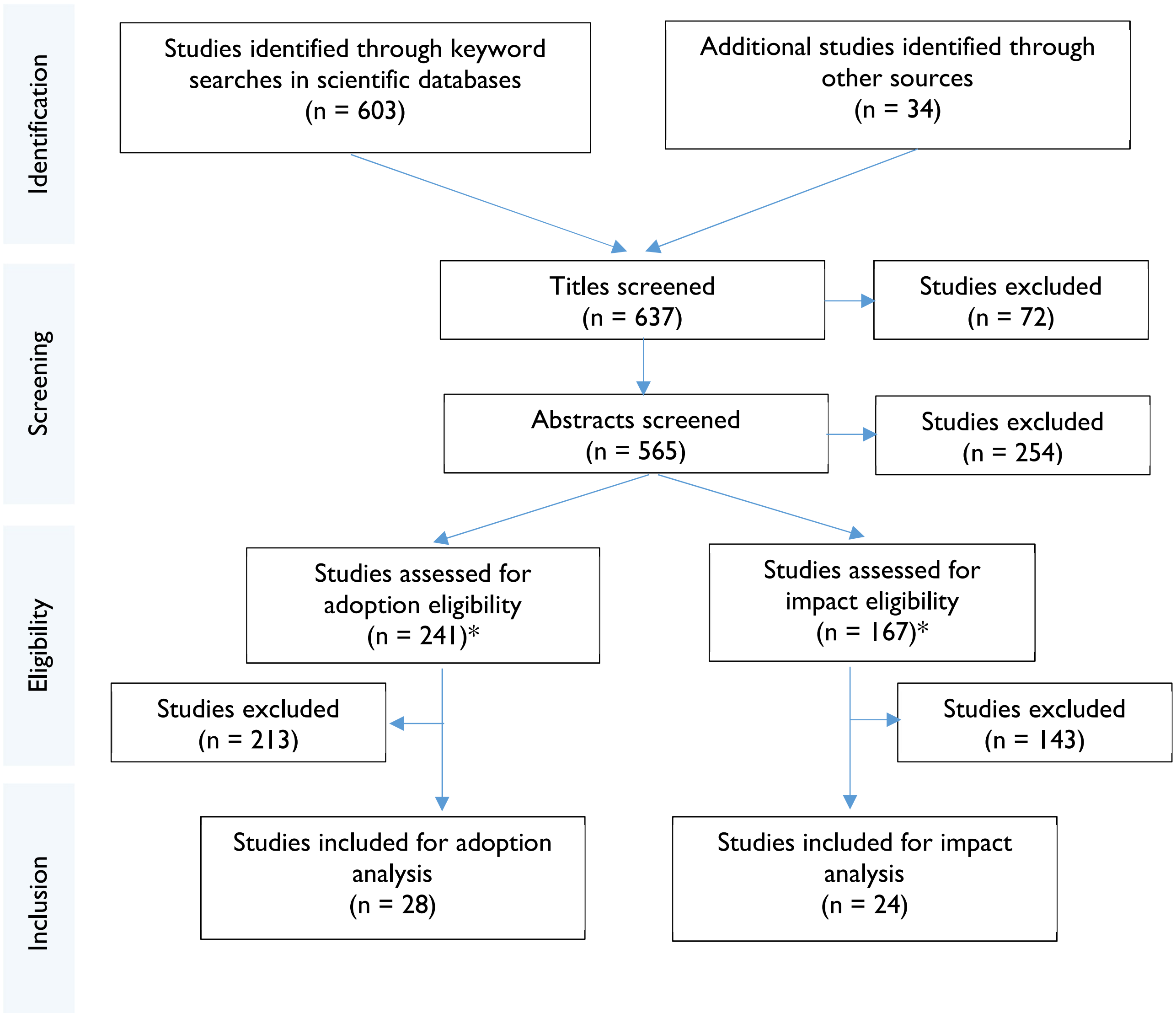
(Study)	Country	Technology	Data sources	Data type	Method to address selection bias	Key output/outcome variable(s)
(Yigezu et al., 2014)	Syria	improved supplemental irrigation	farm survey (n=461)	cross-sectional	none	quantity and value of irrigation water
(Shiferaw et al., 2014)	Ethiopia	improved varieties	farm survey (n = 2017)	cross-sectional	endogenous switching, matching	per capita food expenditure, food security indicators
(Lobell et al., 2013)	India	time of sowing	satellite imageries	time series	none	grain yield
(Yigezu et al., 2013)	Syria	sprinkler irrigation	farm survey (n=385)	cross-sectional	none	water use efficiency
(Grover and Sharma, 2011)	India	zero tillage	farm survey (n=120)	cross-sectional	none	yield, profit, income
(Kassie et al., 2011)	Ethiopia	soil conservation	farm survey (n=148)	cross-sectional	matching	crop income
(Erenstein, 2009)	India, Pakistan	zero tillage	farm survey (n =858)	cross-sectional	within-farm comparison	input use, grain yield, profit
(Erenstein et al., 2008)	India, Pakistan	zero tillage	farm survey (n =391)	cross-sectional	none	yield, cost, profitability

Supplementary Table S3. Effects of Technology Adoption in Wheat

Technology, Study area	Effects documented
Climate-smart agriculture	
Pakistan	Farmers who adopted more climate change adaptation practices had higher food security levels (8–13%) than non-adopters, and the adopters experienced lower levels of poverty (3–6%) (Ali and Erenstein, 2017).
Pakistan	Adopters of climate-risk management strategies realized a higher wheat yield per hectare and income and low poverty levels, compared to non-adopters (Rahut and Ali, 2017).
India	Climate-smart agricultural practices and technologies in smallholder farms generated significant impacts on total production costs and yield in rice-wheat system (Khatri-Chhetri et al., 2016).
Improved varieties/seeds	
Ethiopia	Improved rust-resistant wheat varieties raised effective yields by 8% in comparison to local susceptible varieties (Abro et al., 2017).
Ethiopia	Adoption of improved wheat varieties increased the probability of food security, per capita food consumption, and the probability of attaining the food breakeven and food surplus status (Shiferaw et al., 2014).
Irrigation and water conservation	
Pakistan	Farmers situated at the head of the water source experienced higher wheat yield. Household income levels were higher, and poverty levels were lower with irrigation water availability (Ali et al., 2017).
Pakistan	Farmers without water scarcity problems achieved higher yield and household income and were food secure (Rahut et al., 2016).
Syria	A shift from traditional to improved supplemental irrigation contributed toward the overall effort of water conservation (418 m^3 of irrigation water saved per hectare per year). The shift also had farm-level economic benefits. The improved supplemental irrigation led to the highest farm level economic benefit (25% increase in farm profits) when jointly adopted with sprinkler technologies (Yigezu et al., 2014).
Syria	The wheat farms could maintain the yield level with 9% less irrigation water by replacing the traditional surface canal irrigation schemes with sprinklers (Yigezu et al., 2013).
India	Laser leveling in wheat fields reduced irrigation time by 10–12 hours per hectare per season and improved yield by by 7–9 % in laser leveled fields (Aryal et al., 2015a).
Ethiopia	The net value of crop income for plots with 'Fanya Juu' terraces was lower than for plots without terraces (Kassie et al., 2011).

Conservation agriculture and related technologies	
India	Significant cost savings (14%), pronounced productivity increase (5%), and small but significant improvement in the technical efficiency of production (1%) were associated with the adoption of zero tillage in wheat (Krishna and Veettil, 2014).
India	Zero tillage adoption in wheat increased yield and reduced the cost of production as compared with conventional farms. The practice also increased the income of farmers substantially and reduced poverty (Grover and Sharma, 2011).
India	After the adoption of zero-tillage, CO_2 emission and irrigation water for the wheat crop were reduced by about 19 kg and 127 m^3 per hectare, respectively, as compared to the conventional method of wheat cultivation (Singh et al., 2016).
Syria	Adoption of zero tillage led to a 33% increase in net crop income and a 34% gain in wheat consumption per adult equivalent per year (El-Shater et al., 2016).
India	The average wheat yield was higher under conservation agriculture than under conventional tillage during both bad and average years. However, the yield difference was two-fold higher during the bad year (16% vs. 8%) (Aryal et al., 2016).
India	Zero tillage practices without full residue retention led to a 19% yield gain for wheat over conventional-tillage wheat. The economic benefit from Zero tillage related yield increase and cost savings in wheat production amounted to 6% of total annual income (Keil et al., 2015).
India	Zero tillage adopters could save wheat production costs (USD 79/ha) and increase net revenue (USD 98/ha) as compared to conventional tillage. The benefit-cost ratio under zero tillage was 1.43 against 1.31 under conventional tillage. Shifting from conventional tillage to zero tillage based wheat production reduced Greenhouse Gas emission by 1.5 Mg CO2-eq per hectare per season (Aryal et al., 2015b).
India, Pakistan	Significant resource-saving effects were observed in farmers' fields with zero tillage adoption in terms of diesel, tractor time, and cost savings for wheat cultivation. Water savings were less pronounced (Erenstein et al., 2008).
Farm-machinery	
India	With the adoption of minimum tillage with rotavator, the cost of cultivation and irrigation water used for wheat cultivation reduced. Crop yield, gross and net income, agronomic productivity, and net economic productivity increased (Singh, 2017).
India	Adopters of straw-reaper indicated that technology adoption had positive livelihood effects, including better asset status and higher expenditure on children's education (Kathpalia and Chander, 2017).
Bangladesh	Adoption of power-tiller operated seeding (PTOS) facilitated the highest' energy input use efficiency score' in the rice-wheat farming system, followed closely by bed planting and strip tillage. The difference with traditional tillage was statistically significant for all these technologies (Aravindakshan et al., 2015).

Supplementary Figure S1. Selection of studies for inclusion in the systematic review



Note: The literature selection process was completed in two phases. In the first phase, studies for inclusion in the systematic review were identified through keyword searches. We identified the search terms iteratively. As the first step, a simple search with "Wheat" AND "technology adoption" OR "technology impact"' was performed. Using the insights from this search, additional keywords were identified and included, and the detailed search was performed. In Scopus, for example, the search was done with 'Wheat AND (farmer OR smallholder OR household) AND (technology OR innovation OR intervention) AND (adoption OR acceptance OR use OR impact OR effect OR outcome OR change),' which resulted in 356 documents published between 2008 and 2017.

* Several studies that were examined for impact eligibility were also examined for adoption eligibility.

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