Computers and Electronics in Agriculture 191 (2021) 106516

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Of milk and mobiles: Assessing the potential of cellphone applications to reduce cattle milk yield gaps in Africa using a case study

Christian A. Bateki [*], Thomas Daum, Ana Salvatierra-Rojas, Joachim Müller, Regina Birner, Uta Dickhoefer [1]

Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim, 70599 Stuttgart, Germany

ARTICLE INFO

Keywords:
ICT applications
Milk yield gaps
Dairy cattle
Digital agriculture
Sub-Saharan Africa

ABSTRACT

There are growing expectations that Information and Communication Technology (ICT) applications could help improve on-farm yields amongst smallholder farmers in developing countries, and consequently, food and nutrition security. However, few studies have quantified the actual contribution of ICT applications on farmers' yields, and these studies predominantly focused on crop production. We assessed the potential of ICT applications to close milk yield gaps among small- and medium scale dairy cattle farmers in Africa. First, we developed a theoretical framework summarizing biophysical and socio-economic constraints that foster milk yield gaps and discussed which constraints can be addressed using ICT applications. Second, using a case study of a feeding advice application for dairy cattle pre-tested with farmers in rural Kenya, we analyzed how much stand-alone the application could contribute to close dairy cattle milk yield gaps. Our findings suggest that ICT applications could help address some existing biophysical and socio-economic constraints fostering milk yield gaps, including data collection for breeding programs, feeding management advice, and facilitating access to markets and capital. Our stand-alone ICT application closed yield gaps by 2 % to 6 % on representative farms. Several factors may explain the limited actual contribution of selected ICT applications to reduce existing milk yield gaps, including the quality of the input data and models used in ICT applications, and more structural constraints that cannot be addressed by digital tools. Therefore, although ICT applications could help address constraints to achieving higher milk yields on dairy farms, a significant contribution to improve yields may only be achieved when conditions surrounding their use are adequate.

1. Introduction

Policymakers, donors, and researchers emphasize the potential of information and communication technologies (ICTs) such as smartphone applications to ensure food security and enhance the livelihoods of smallholder farmers in developing countries (Baumüller, 2018; Daum, 2018). Examples of such applications are *Hello Tractor,* which helps farmers to access tractors in Nigeria[2]; *M−Pesa*, which allows farmers to perform cashless money transactions in Kenya[3]; and *Farmcrowdy,* which connects farmers to sponsors in Nigeria[4]. While there is much hope around the potential contribution of such applications, there are few discussions on whether they can help smallholder farmers in developing countries (Baumüller, 2018). To systematically examine the potential contribution of ICTs to farmers' livelihoods, we assessed the theoretical and practical contribution of cellphone and smartphone applications (hereafter referred to as ICT applications) to close yield gaps amongst smallholder farmers in developing countries. We focused on yields because they are an essential determinant of both, food security and livelihoods of farmers. Also, since studies (Tittonell and Giller, 2013; Van Ittersum et al., 2013) have shown high yield gaps in Sub-Saharan Africa (SSA), we chose it as the geographical focus of the present paper.

Yield gap studies compare the maximum yield achievable under best management practices with the actual yield achieved by average

* Corresponding author at: Division for Agriculture and Rural Development, Unique Forestry and Land Use GmbH, 79098 Freiburg, Germany.
E-mail address: chrislarabie2005@yahoo.fr (C. A. Bateki).
[1] Current address: Institute of Animal Nutrition and Physiology, Christian-Albrechts-Universität zu Kiel, 24098 Kiel, Germany.
[2] https://www.hellotractor.com/home
[3] https://www.vodafone.com/content/index/what/m-pesa.html#
[4] https://www.farmcrowdy.com

https://doi.org/10.1016/j.compag.2021.106516
Received 16 September 2020; Received in revised form 9 October 2021; Accepted 22 October 2021
Available online 5 November 2021

farmers (FAO and DWFI, 2015). As such, the yield gap can be explained by different constraints that prevent the average farmers from achieving the maximum yield associated with best management practices. Early yield gap studies have focused on biological and technical constraints, which could be overcome, for example, with breeding and better input supply (Snyder et al., 2017). The sole focus on biological and technical constraints to close yield gaps has been questioned by authors, including Beddow et al. (2015) and Pingali and Heisey (2001). They emphasized the need to address economic constraints to close yield gaps and argue that farmers maximize utility (e.g., by increasing profits or minimizing risks) rather than yields. More recent yield gaps studies such as Snyder et al. (2017) have thus widened the yield gap concept to include social, economic, and political constraints. This broadened concept allows for a better understanding of constraints to closing yield gaps and, thus, entry points for policy interventions as well as entry points for ICT applications to close yield gaps.

In the present paper, we focused on dairy cattle milk yield gaps because, unlike the crop production systems in SSA for which multiple yield gap studies exist, only a few studies (Herrero et al., 2016; Mayberry et al., 2017) exist for livestock production systems. As such, in terms of yield gaps, livestock systems have been described as "severely under-researched" (Henderson et al., 2016). The neglect of livestock research persists although eggs, meat, and milk are essential for food, nutrition, and income security of smallholder farmers in SSA (Delgado, 2003; Delgado et al., 1999). Some studies have shown an enormous potential to close milk yield gaps in SSA, for example, by improved cattle nutrition and breeding (Mayberry et al., 2017) and better access to inputs and markets (Henderson et al., 2016).

Therefore, the present study assessed the potential of ICT applications to reduce milk yield gaps among small- and medium scale dairy cattle farmers in SSA. First, we developed a theoretical framework explaining the reasons for existing dairy cattle milk yield gaps and discussed which constraints could be addressed with the help of ICT applications. Then, using a case study focusing on feeding advice application developed for dairy cattle and pre-tested with farmers in rural Kenya, we quantified how much such (stand-alone) ICT applications could contribute to closing milk yield gaps in practice. The findings from the present study will be of relevance for farmer organizations, extension agents, consultants, researchers, and policy makers involved or associated with the dairy sector in SSA.

2. Theoretical potential of ICT applications to reduce milk yield gaps

2.1. Defining the milk yield gap

Akin to crop production yield gaps (Roetter et al., 1998), the milk yield gap compares the milk yield of different benchmarks (i.e., potential yields) and the average actual milk yield of a defined farmer category in a specific geographical region. In Fig. 1, we proposed a milk yield gap framework that spans from the theoretical potential milk yield to the post-harvest milk yield. The theoretical potential yield is the highest benchmark to which farmers' yields could be compared. It is usually modeled and achievable only under optimum conditions (i.e., environmental and management) and by cattle breeds with the best genetic potential (FAO, 2000). The next lower benchmark is the milk yield achievable under very controlled conditions on experimental stations (Gomez et al., 1979). Comparing on-farm milk yields with either of the above benchmarks neglects the variable production purposes and multiple constraints (e.g., biophysical, and socio-economic constraints) that on-farm realities impose (Rockström and Falkenmark, 2000). Thus, such comparisons may provide little or no relevant guidance for decision-making by policymakers, farmers, and development practitioners in SSA.

For realistic guidance for closing milk yield gaps in SSA, the average actual milk yield of a defined farmer category can be compared to benchmarks lower than the yields on experimental stations, including the milk yield on the potential and economic farms. The potential farm milk yields can be derived from commercial farms belonging to the top 10 % milk producing farmers within a specific region (Mayberry et al., 2017). However, striving for the potential farm milk yield may not always be economic because farmers maximize utility and not yields (Fischer et al., 2009). Focusing on economically attainable milk yields could address the latter shortcoming that arises with focusing on the potential farm milk yield (Fischer et al., 2009). The economically attainable milk yield is reached when farmers produce milk at levels that ensure maximum profits, i.e., when marginal revenue equals marginal costs, under current market conditions (Beddow et al., 2015; Fischer et al., 2009).

Below the economic farm milk yield is the actual farm milk yield, which refers to the average production observed on-farm in a specific region. The actual milk yield is the result of farmers producing under

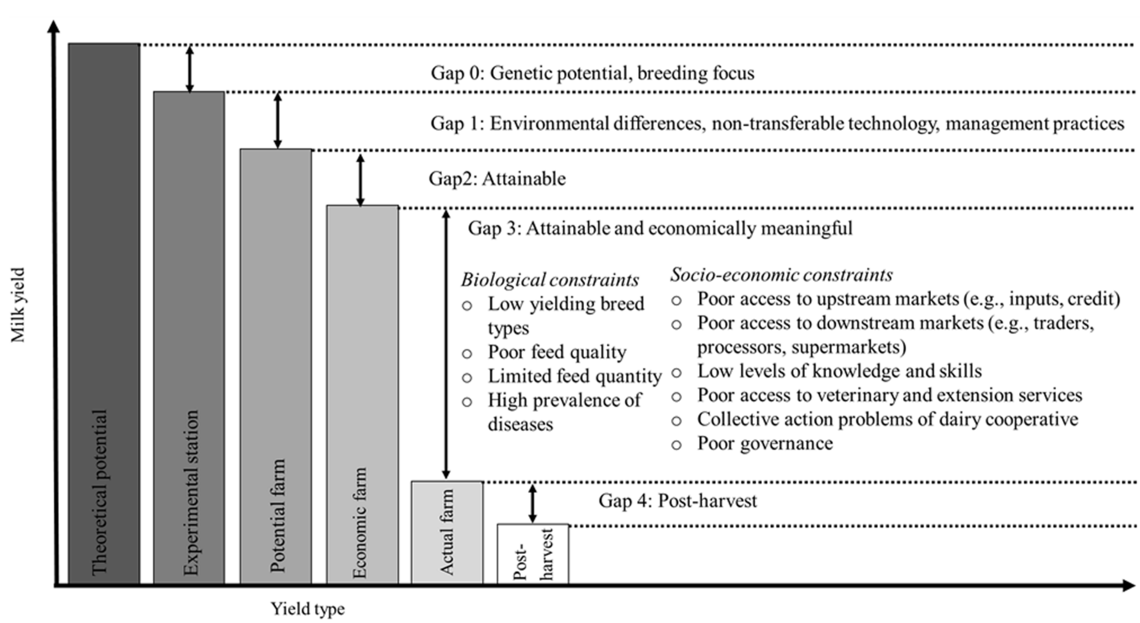

Fig. 1. Dairy cattle milk yield gap framework.

locally prevailing biophysical (e.g., access to pastures, water, and prevalence of pests and diseases) and socio-economic (e.g., access to markets, capital, and extension services) conditions (FAO, 2000).

Yield gap frameworks for crop production systems mostly end with the actual farm yield. Instead, we suggest a “post-harvest milk yield” as the lowest benchmark in the milk yield gap framework given the highly perishable nature of milk (Gustavsson et al., 2011). Post-harvest milk yield losses are common across all farm types and the various benchmarks shown in Fig. 1 but these vary in magnitude. Some of the largest losses occur during post-harvest handling, storage, and distribution of milk in developing countries, with up to 30 % of harvested milk being lost amongst small- and medium scale dairy cattle farmers (Salvatierra-Rojas et al., 2018). Therefore, omitting this benchmark in a milk yield gap framework could prevent stakeholders from identifying and solving constraints related to post-harvest milk losses, and thus hamper the improvement of farmers’ livelihoods and food security.

For the present study, we focused on the yield gap in milk production of dairy cattle between the actual and economically attainable yields, because this is the locus of control for farmers, policymakers, and development practitioners (Rockström and Falkenmark, 2000). As such, the milk yield gap in percent was estimated according to Eq. (1) below.

$$MY_{gap} = \left(\frac{(MY_{economicfarm} - MY_{actualfarm})}{MY_{actualfarm}}\right)*100 \quad (1)$$

where MY_{gap} is the milk yield gap (kg/animal/day), $MY_{economic\ farm}$ the observed milk yield on economic farms (kg/animal/day), and $MY_{actual\text{-}farm}$ the observed milk yield on average farms (kg/animal/day).

2.2. Constraints explaining milk yield gaps

2.2.1. Biophysical constraints of milk yields

Biophysical constraints have a significant effect on milk yields of dairy cattle. For example, there is a clear consensus that the choice of cattle breed determines milk yields attainable per cow and year, with cross-bred cows performing better than indigenous cows (Abeygunawardena and Dematawewa, 2004; Bateki et al., 2020; Jenet et al., 2004). Also, diseases such as East Coast fever, mastitis, and trypanosomiasis negatively affect milk production (Bebe et al., 2003). For example, FAO (2014) showed that mastitis could decrease milk yield by up to 33 % per udder quarter infected. Nutritional deficiencies and imbalances are standard on most small- and medium scale dairy farms in SSA because of extreme seasonal variations in availability and quality of feed resources (Maleko et al., 2018; Onyango et al., 2019), resulting in low milk yields per cow. Thus, the lack of access to adequate quantities of quality feed resources (e.g., crops residues, fodder legumes, and concentrates) constraints actual farms from achieving the milk yields attained on economic farms (Duguma and Janssens, 2016; Duncan et al., 2013; Maleko et al., 2018). Lastly, access to sufficient drinking water for cattle could constraint milk yields on small- and medium scale dairy farms (Little et al., 1980), mainly because such farms often lack water storage facilities (Maleko et al., 2018).

2.2.2. Socio-economic constraints of milk yields

Several socio-economic constraints limit the ability of actual farms to attain the milk yields observed on economic farms. Market access plays a vital role, given the highly perishable nature of milk compared to most crops (Henderson et al., 2016). Duncan et al. (2013), stratifying output markets by attractiveness and reliability, showed that farmers with access to medium quality markets produced 675 L of milk per year, whereas farmers with access to high-quality markets produced 1200 L per year. This difference in the level of production may be related to the fact that the incentive to own exotic breeds, to provide good feed, and thereby to produce large quantities of milk diminishes with low milk prices, high transaction costs for marketing, and risky markets (Maleko et al., 2018).

Moreover, a lack of roads, processing and storage facilities, as well as electricity, results in significant post-harvest milk losses (Duncan et al., 2013), which can discourage farmers from closing milk yield gaps. Also, milk yield gaps in dairy cattle may remain large because of poor access to and high prices of production inputs like feed and vaccines (Maleko et al., 2018). Similarly, lack of access to credits may limit farmers’ ability to close milk yields gaps when some inputs such as improved dairy cattle breeds remain unaffordable (Maleko et al., 2018).

Institutional constraints to closing this yield gap may include a lack of access to animal health care and extension support services (Awa and Achukwi, 2010; Mockshell et al., 2014), and formal feed and pasture seed quality control (Maleko et al., 2018). Similarly, knowledge and skills on fodder production, feeding strategies, herd records keeping, and budgeting for the periods of feed scarcity (Maleko et al., 2018; Owen et al., 2012) all play a role in determining what milk yield a farmer can achieve. Traditions and culture may also contribute to sustained milk yields gaps between economic and actual farms because they influence dairy cattle management practices. For example, farmers may prefer low yielding indigenous breeds to the high yielding improved breeds due to the cultural acceptance that indigenous breeds have (e.g., as gifts, dowry, and even wealth status) (Ainslie, 2013). Also, cattle may be kept for manure or draught power to support crop production, which may lead to trade-offs at the expense of milk yields (Bebe et al., 2003). Gender issues could also influence the milk yield gap between economic and actual farms as suggested by Henderson et al. (2016), who found that female-headed households have larger milk yield gaps (i.e., due to lower access to markets and extension service, and a higher risk aversion) than male-headed households.

2.3. Entry points for ICT applications to reduce milk yield gaps

Numerous entry points exist for ICT applications to address the constraints mentioned above that explain the milk yield gaps between actual and economical dairy cattle farms in developing countries (Table 1). From collecting the robust data currently lacking for dairy cattle breeding programs in the Tropics (McGill et al., 2014), to enhancing access to advisory services for improved feeding, disease control, and markets, ICT applications could contribute to close milk yield gaps in SSA. Nevertheless, most ICT applications we identified, mainly focused on providing general advice to farmers (Table 1), and thus dealing with the so called “low-hanging fruits” (Aker et al., 2016).

While several promising entry points for ICT applications exist, little is known about the real contribution of such ICT applications (Baumüller, 2018). Some ICT applications providers for example, *iCow*, have reported an average increase in milk yields of 2 to 3 l per cow, and a reduction in calf mortality and veterinary costs amongst its users (Kahumbu, 2012). However, to our knowledge until now, no scientific study has attempted to quantify the potential contribution of ICT applications to reduce milk yield gaps. Thus, in the next section, employing a smartphone application for optimizing dairy cattle diets, we quantified the potential contribution of this stand-alone ICT application to closing the milk yield gap.

3. The actual potential of ICT applications to reduce milk yield gaps: Case study using a ration formulation “app” in rural Kenya

Inadequate cattle nutrition ranks high amongst the reasons for low milk yields amongst small- and medium scale dairy cattle farmers in developing regions such as East Africa (Mayberry et al., 2017; Ngongoni et al., 2006). Several feeding-related strategies (Bateki et al., 2020) are available to dairy farmers to improve cattle nutrition in East Africa. Yet, most dairy farmers either under- or over-supply nutrients and energy to their animals (Bwire and Wiktorsson, 2003; Place et al., 2009), thus resulting in low milk yields. Within this context, a ration formulation “app” that integrates existing scientific knowledge was developed to help farmers and advisory services satisfy the nutrient and energy

Table 1
Identified entry points for ICT applications to reduce milk yield gaps.

Constraints	ICT application entry point	Examples in developing countries
Bio-physical		
Breed type	Collection of data for breeding programs by tagging animals with radio-frequency identification devices to record animal data including animal status, health and performance	*Herdman* in India (Bhattacharya, 2017)[1]
Disease control and management	radio-frequency identification based traceability system	*Namibian Livestock Identification and Traceability System* (Deichmann et al., 2016)
	Crowdsourcing for disease monitoring and warning	*VetAfrica*, a smart-phone application (CTA, 2017)
	Monitoring livestock herds	*Jaguza*, a Ugandan mobile service[2]
Pasture and water	Finding pastures and waterholes for livestock	*Afriscout*, a Kenyan app providing localized maps on water and vegetation conditions[3] *myAnga*, a Kenyan app providing data on weather and forage conditions[4]
	Providing hyper-localized weather forecasts	Several projects but mostly at the pilot stage (Caine et al., 2016)
Feed	Optimizing dairy cattle rations	*Fodjan* feeding app for dairy cattle On-farm Feed Advisor Tool (ILRI)[5]
Constraints	**ICT application entry point**	**Examples in developing countries**
Socio-economic		
Access to upstream markets (inputs, credit, insurance)	Crowdfunding for acquiring improved animal breeds	*Farmable*, a Ghanaian smart-phone application which links urban consumers with farmers to help them fund purchase of improved dairy cattle breeds[6]
	Linking farmers with lenders	*DrumNet*, a Kenyan ICT platform that links farmers with lenders (banks, microfinance, input supplier, processors, traders) and provides risk monitoring to enhance access to microcredits
Access to downstream markets (traders, cooperatives, processors, supermarkets)	Linking farmers and consumers	*Farmable*, a Ghanaian smart-phone application, links farmers with urban consumers
	Traceability system using radio-frequency identification or blockchain to link farmers with supermarkets	-
	Providing market information to farmers and consumers	*ESOKO*, a smart-phone application active in several countries, providing market data[7]
Knowledge and skills	Short message service alerts with general or cow-specific advice	*iCow,* a Kenyan mobile application that sends standardized short message service (SMS) alerts on feeding, disease control, fertility management, and cow milking based on dairy cattle calendars (Gathigi and Wattis, 2013)
	Fertility management based on body temperature and physical activity	*Jaguza*, a Ugandan mobile service[8]
Constraints	**ICT application entry point**	**Examples in developing countries**
Socio-economic		
Herd management software	Supporting the management of herds (e.g., focused on fertility management and economics)	*Farmtree*, a herd/stable management software developed by Inhof Technologies in India[9]
Access to veterinary services and extension	Diagnosis of diseases and provision of advice for treatment required	*VetAfrica*, a smart-phone application for diagnosing diseases and obtaining advice (CTA, 2017)
	Tracking animal health	*Cowtribe*, a Ghanaian smart-phone application to schedule veterinary treatments and track health statistics[10] *Herdman*, an Indian smart-phone application to record data related to feeding, calving, weight, health, diseases, yields using QR codes, which can be used to guide veterinary officers[11]
Collective action problems of dairy cooperative	ICT application to overcome collective action problems of dairy cooperatives	In India, apps are used for the collection and testing of milk at cooperatives and managing the payouts to farmers (McNamara et al., 2017)
Governance problems	Monitoring public or private veterinary officers and artificial insemination agents	*Herdman*, an app requiring veterinarians and insemination agents to scan QR codes of cows to prove their visits in India (Bhattacharya, 2017)[12]
	Traceability system using radio-frequency identification or blockchain for ensuring feed and animal drug quality	-

[12] http://www.infovet.in/
[1] http://www.infovet.in/
[2] https://jaguzafarm.com/
[3] https://www.pciglobal.org/afriscout/
[4] https://play.google.com/store/apps/details?id = com.myanga.android.climark&hl = en
[5] https://www.ilri.org/research/projects/farm-feed-advisor
[6] http://www.farmable.me/
[7] https://esoko.com/
[8] https://jaguzafarm.com/
[9] http://inhof.in/
[10] https://www.cowtribe.com/
[11] https://play.google.com/store/apps/details?id = herdmanmobivet.herdman&hl = en_IN

requirements of their animals using locally available feed resources.

3.1. The fodjan ration formulation "app" for dairy cattle farmers

fodjan[5] is an algorithm-based web platform developed to help farmers in temperate regions manage feed stocks and optimize livestock nutrition. The fodjan web platform hosts different feed models for estimating the energy and protein requirements of dairy cattle. The University of Hohenheim developed a "Tropical model", specific to dairy cattle in the (Sub-)Tropics (Bateki and Dickhoefer, 2018), and implemented it on the fodjan web platform.

The fodjan ration formulation "app" for dairy cattle farmers in the (Sub-)Tropics is composed of three components (Bateki and Dickhoefer, 2018): (1) a calculator module (Fig. 2) that estimates the daily metabolizable energy and protein requirements for local *Bos indicus* breeds, crossbreds (*Bos indicus* × *Bos taurus*), and exotic breeds (*Bos taurus*); (2) a feed library summarizing the nutritional characteristics of over 230 (sub-)tropical ruminant feedstuffs. Feed specific data like feed costs must be entered by the users since these vary across different locations; and (3) a solver that uses various algorithms developed by fodjan GmbH to optimize ration composition for feeding costs, cow rumen health, and increased milk yield. Integrating information from the above three components, the fodjan ration formulation "app" suggests 3 – 5 rations, each optimized for a different production objective (e.g., minimum feed costs, maximum animal performance, or improved rumen health) depending on the user-defined feedstuffs.

3.2. Potential of the fodjan ration formulation "app" to close milk yield gaps on-farm in Western and Central Kenya

3.2.1. Sample population and the milk yield gap

The present study used existing feeding and performance data collected by convenience sampling from 105 *B. taurus* cows and heifers on 21 small- and medium scale dairy cattle farms in Western and Central Kenya (Doldt, 2019). From this data, 63 cattle whose complete details (e.g., breed, body-weight, parity) were available were selected and grouped into three groups according to parity (i.e., number of times a cow has calved). Within each parity group (Table 1), we identified farms achieving the highest daily milk yield and assigned them to the economic farm category as per our milk yield gap framework (Fig. 1). The maximum daily milk yields achieved on economic farms were 21, 19, and 21 kg/animal for parity groups 1, 2, and 3, respectively. Likewise, farms with daily milk yields close to the average milk yields observed within each parity group (Table 2) were assigned to the actual farm category. Cows in the actual farm category produced (i.e., mean milk yield) 10 kg/animal/day of milk for all three parity groups (Table 2). Therefore, the daily milk yield gaps retained for the three parity groups in our study were 11 kg (110 %), 9 kg (90 %), and 11 kg (110 %) per animal for parity groups 1, 2, and 3, respectively.

3.2.2. Simulating closures in milk yield gap using the fodjan ration formulation "app"

Rations are normally formulated using the amount and nutritional quality of available feed resources, as well as the body-weight, productive performance and feed intake data from representative animals in a herd (White and Capper, 2014; Žgajnar et al., 2009). Accordingly, data (Table 3) from three cows, each representing one of the three parity groups in our dataset were entered into the fodjan "app" to estimate their energy and nutrient requirements.

The fodjan feed library was updated using data on the nutritional characteristics (Doldt, 2019) of the different feedstuffs offered on each farm (Table 4). Next, the fodjan "app" evaluated the dry matter intake, protein and metabolizable energy concentrations in the ration, and metabolizable energy requirements of the representative animal on each farm, to provide a milk yield per ration report. Then, the first restrictive parameter of either the metabolizable energy or utilizable crude protein supply in the ration was retained as the predicted daily milk yield.

The accuracy of predictions from the fodjan "app" for the present study was assessed using the relative mean bias (Cochran and Cox, 1992), as shown in Eq. (2) below.

$$Relativemeanbias = \frac{(ReportedMY - PredictedMY)}{ReportedMY} \bullet 100 \quad (2)$$

Last, we optimized the rations on each farm for improved performance using the fodjan "app".

3.2.3. Results of milk yield gaps closure simulations in the fodjan ration formulation "app"

3.2.3.1. Milk yield report and daily milk yield predictions from the fodjan "app". The milk yield report (Table 5) from the fodjan "app" showed that the daily milk yields of cows on all three farms were limited by the metabolizable energy concentration of the rations offered. Yet, the utilizable crude protein concentration of the rations suggest that cows could produce more milk. The fodjan "app" predicted daily milk yields with a relative mean bias of 6 %, 22.5 %, and 57 % compared to yields reported by farmers for cows on farms A, B, and C, respectively (Table 5).

3.2.3.2. Evaluation of optimized rations from the fodjan "app" and their impact on cattle milk yields. Optimizing rations for more milk using the fodjan *"app"* resulted in increases in daily milk yields of 0.2 kg, 0.4 kg, and 0.1 kg for cows on farms A, B, and C, respectively (Table 6). The increase in daily milk yields also resulted in a decrease in feed cost per kg of milk on all three farms (Table 6). Furthermore, optimizing only for healthier rations suggested that cows would produce less, but at reduced feed costs than what the rations used by the farmers in our data afford. Also, optimizing for healthier and cheaper rations resulted in similar (Farm A) and greater (Farms B and C) milk yields but lower feed costs per kg of milk produced for the optimized than the reported rations (Table 6).

4. The potential of ICT applications to reduce cattle milk yield gaps

4.1. Validity of the fodjan "app" to reduce milk yield gaps amongst dairy cattle smallholders

Establishing the validity (i.e., how closely reality is reflected) of any ICT tool is an essential first step to assess its potential contribution to close milk yield gaps. In our study, the validity of the fodjan "app" was evaluated based on the accuracy (i.e., relative mean bias) with which milk yield (kg/cow/day) was predicted. A satisfactory prediction for the daily milk yield should have a relative mean bias of ≤ 20 % (Faverdin et al., 2011). Accordingly, the fodjan "app" predicted the daily milk yield acceptably only for animals on farm A.

The high relative mean biases (i.e., 22.5 % and 57 % of the observed daily milk yield) for animals on farms B and C may be due to either a systematic error (i.e., related to weaknesses in the feed model in the app) or random error (i.e., errors associated with the input data used) (Meyer et al., 1989). The main parameters that changed when simulating the farms in the present study were the input data (i.e., body-weights, feed intake, and the reported daily milk yields) rather than parameters in the tropical feed model. Since the accuracy in predictions of the daily milk yield from farm A was very good, we suggest that the leading cause of the poor accuracy in daily milk yield predictions for farms B and C was due to random errors. The daily feed intake and milk yield data used in the present study were estimated using information reported by farmers

[5] https://fodjan.de

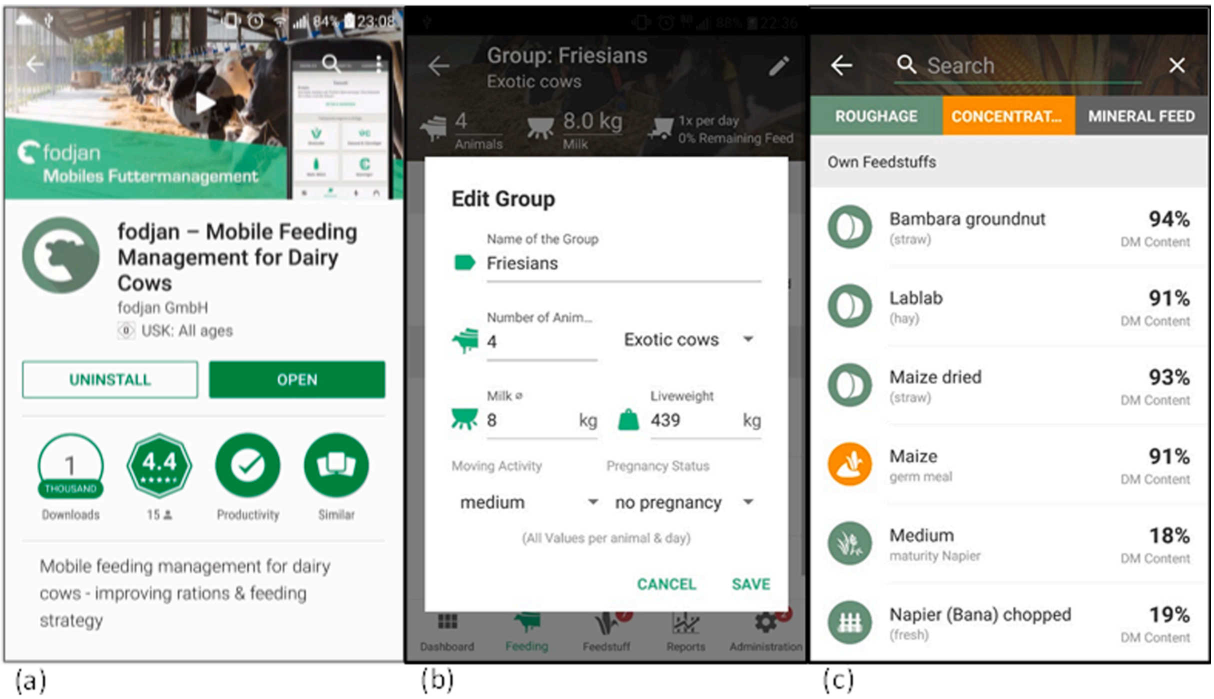

Fig. 2. Screenshots of the fodjan ration formulation application: (a) home screen of the application after installation on a smartphone; (b) calculator module interface for entering animals' data to estimate their daily metabolizable energy and protein requirements, and (c) overview of the feed database interface showing some tropical feedstuffs.

Table 2
Descriptive statistics for animals in different parity groups used to evaluate the potential performance of the fodjan ration formulation "app".

Parameter	†n	Mean	‡SD	Maximum	Minimum	Median
Parity = 1						
Body-weight, kg	17	456	107	699	318	454
Milk yield, kg/animal/day	17	10	4	21	3	10
Days in milk (n)	15	299	236	913	45	263
#DMI, kg/animal/day	17	19	6	27	10	19
Parity = 2						
Body-weight, kg	29	432	83	597	281	420
Milk yield, kg/animal/day	29	10	5	19	2	9
Days in milk (n)	27	257	132	544	7	295
#DMI, kg/animal/day	29	18	4	27	10	18
Parity ≥ 3						
Body-weight, kg	17	420	85	573	261	414
Milk yield, kg/animal/day	17	10	6	21	1	9
Days in milk (n)	16	233	175	730	32	211
#DMI, kg/animal/day	17	17	4	26	10	18

† Number of animals considered for summarizing the specific parameter;
‡ standard deviation, #voluntary dry matter intake of animals.

Table 3
Summary animal input data for farmers selected for each of the three groups defined in this study.

Parameter	Actual farms in Western and Central Kenya*		
	Farmer A	Farmer B	Farmer C
Parity group (n)	1	2	≥ 3
Breed	Friesian	Friesian	Friesian
Physiological status	Cow	Cow	Cow
Body-weight, kg/cow	382	581	370
Dry matter intake, kg/cow/d	14.3	12.6	10.3
Reported milk yield, kg/cow/d	10.0	8.0	9.0

* Each cow representing one of the three parity groups was allocated to a farmer to more accurately represent how the data was handled in the "app".

rather than measured data (Doldt, 2019). This may explain the loss in accuracy because farmers may misjudge the required data, and thus overestimate or underestimate some figures, leading to wrong advice. Consequently, it is vital to use measured data in future studies that aim at doing similar simulation exercises.

Due to the potential weakness of the input data used in the present study, we considered the relative bias (i.e., 22 % of the observed daily milk yield) in milk yield predictions for farm B as acceptable for the present simulation exercise. Thus, the potential of the fodjan "app" to reduce dairy cattle milk yield gaps is hereafter discussed based on the results from farms A and B.

4.2. Extent to which ICT applications could help reduce cattle milk yield gaps amongst farmers in Sub-Saharan Africa

Several authors (Kiambi, 2018; Moyo et al., 2015; Verdier-Chouchane and Karagueuzian, 2016) have alluded to the immense potential contribution of ICT applications to agriculture in SSA. Using the fodjan "app" in the present study resulted in 2 % (i.e., from 110 % to 108 %) and 6 % (i.e., 90 % to 84 %) decrease in the dairy cattle milk yield gaps of cows on farms A and B (Fig. 3) without any additional feed inputs.

These findings showed that although ICT applications may improve several aspects of feed management for milk production, stand-alone ICT applications may not significantly increase daily milk yields as expected by various stakeholders. Several factors hampering the full potential of ICT applications in SSA have already been discussed in the literature (CTA, 2019; Daum et al., 2021). Yet, two main factors could explain the low contribution of ICT applications to reduce cattle milk yield gaps amongst farmers in SSA, including the capacity of ICT applications and the socio-cultural and economic contexts of the users.

Table 4
Cost and nutritional characteristics of different feedstuffs used by farmers in the present study.

Selected farm (parity group)	Feedstuffs offered	Cost KSh/kg as fed[§]	DM [g/kg FM[¶]]	Chemical composition [g/kg dry matter][#]					ME [MJ/kg DM]
				CP	uCP	NDF	ADF	ADL	
Farm A (1)	Dairy meal (Pascho*)	34.0	910	134	135	495	316	98	9.7
	Natural grass (dried)	1.5	640	103	114	641	373	140	7.0
	Napier grass (fresh)	3.0	170	94	103	639	426	140	6.3
Farm B (2)	Dairy meal (Pembe*)	34.0	930	150	168	376	213	90	11.4
	Fresh lucerne	33.3	230	164	149	497	338	95	8.1
	Maize germ	20.0	920	50	108	314	160	40	9.2
	Maize silage	6.0	410	61	104	619	385	84	7.5
	Rhodes grass hay	16.6	880	56	98	702	413	56	6.7
Farm C (≥3)	Dairy meal (Alliance feeds*)	34.0	920	150	154	406	220	99	10.0
	Fodder mix	22.0	570	90	101	654	415	140	6.4

[§]KSh: Kenyan Shillings obtained from local Kenyan markets, 108 KSh was (22.08.2020) equivalent to 1 USD (https://www.xe.com/currencyconverter/convert/?Amount = 1&From = USD&To = KES); ¶FM: fresh matter; [#]DM: dry matter, CP: crude protein, uCP: utilizable crude protein, NDF: neutral detergent fibre, ADF: acid detergent fibre, ADL: acid detergent lignin, ME: metabolizable energy; and *brand name for different dairy meal producers.

Table 5
Milk yield per ration report for the animals in three parity groups on representative farms in Western and Central Kenya.

Parameter	Actual farms in Western and Central Kenya		
	Farm A	Farm B	Farm C
Parity (n)	1	2	≥3
Breed	Friesian	Friesian	Friesian
Dry matter intake, kg/cow/day	14.3	12.6	10.3
Actual milk yield, kg/cow/day	10.0	8.0	9.0
ME driven milk yield (rMB), kg/cow/day[1]	9.4 (6 %)	6.2 (22.5 %)	3.8 (57 %)
uCP driven milk yield, kg/cow/day[1]	14.2	13.1	11.5

[1] ME is the metabolizable energy and uCP the utilizable crude protein driven milk yields are those predicted by the fodjan "app" based on their respective concentrations in the rations. The predicted daily milk yield from the app is then the lower of either the energy or the protein driven milk yields. As such, the fodjan predicted milk yields for all parity categories in Table 4 were limited by the metabolizable energy contents of the rations. The rMB is the relative mean bias, and it estimates how much the predicted daily milk yield from the fodjan "app" differs from the milk yield reported by farmers (i.e., actual milk yield) in our data.

The capacity of ICT applications to reduce cattle milk yield gaps in SSA depends on three pillars, including (i) data collection and entry, (ii) data processing and optimization, and (iii) feedback provision. Regarding data collection and entry, ICT applications often require upfront entry of animal and farm data (e.g., milk yield, body-weights, and feeds available). The data entered by the farmer into the application should be correct and comprehensive. Incorrect data will lead to unreliable outputs from any ICT application, and incomprehensive data may limit the scope of action of the application. For example, in the present study, farmer B had a more comprehensive list of feedstuffs used than farmers A and C (Table 6), thereby allowing for more scope in optimizing the animal's rations and thus a higher reduction in the milk yield gap for the former than the latter. As such, one drawback in the present study is that the ICT application was limited in its scope to optimize the rations for increased milk yields by the limited choice of feed resources, and the low to average nutritional quality of the feedstuffs available to the farmers. Thus, there may be a larger potential to reduce the milk yield gap is sufficient feed resources of good nutritional quality are used.

The data processing and optimization pillar builds on the biophysical and socio-economic knowledge within an ICT application to generate recommendations for users. As such, ICT applications always function within the boundaries defined by the developers and users. For example, the fodjan "app" afore presented enables users to optimize rations for lower costs, higher milk yields, and improved rumen health. However, dairy cattle production systems comprise of several components, such that farmers' decision-making matrices may typically go beyond dairy production to include crop production, as well as off-farm activities (Bateki et al., 2019) Thus, trade-offs, as well as synergies between different production resources need to be considered. For example, as land and labor allocated to feed production cannot be used for crop production (Maleko et al., 2018), maximizing profits from milk production may be associated with a decline in overall farm profits. As such, allowing the data processing and optimization to integrate data from different areas of production could widen the production optimization scope of ICT applications used by farmers in SSA. Such data integration between ICT applications could be done via the coupling of different applications, thereby enabling holistic and realistic ICT supported decision making at farm level. Moreover, concerning the data processing/optimization, questions around the objective function of farmers arise. As noted above, farmers maximize utility (such as profits) and not milk yields, which should be considered by the ICT applications. As observed by Mayberry et al. (2017), the potential of livestock interventions to reduce milk yield gaps diminishes when accounting for economic criteria because some interventions reduce the yield gaps but increase marginal costs more than marginal revenue.

Regarding the feedback provision pillar (i.e., final advice given), several aspects need to be considered when exploring how ICT applications could contribute to closing the gaps in cattle milk yields in SSA. First, biophysical and socio-economic constraints determine the milk yield gap amongst farmers (see section 2.2). Whilst ICT applications may contain the knowledge to overcome certain constraints; they do not directly modify the bio-physical components such as the animals' genetics and feed quality used (Moyo et al., 2015). Thus, for any ICT application to help close dairy cattle milk yield gaps in SSA, farmers should be willing and able to modify, and improve existing production practices as their means allow, to comply with the suggestions from ICT applications. Thus, one needs to distinguish between the ability of ICT applications to suggest solutions to constraints (e.g., diagnosing diseases and suggesting better feeding) identified on-farm and the ability of the farmers to implement those solutions proposed. Second, there is the issue of information sources and trust on the part of farmers (Aker et al., 2016). Advice provided via ICT applications must not only be accurate and reliable, but they should also be backed by persons who have the farmers' trust (e.g., extension agents or other farmers), else farmers may not take up the advice. More so, it is essential that the advice or recommendations provided by ICT applications be within the scope of what farmers can implement using the resources available and accessible to them. Hence, the potential of ICT applications to reduce cattle milk yield gaps depends not only on the digital solutions themselves and their purposes, but also on the analogous context of the farmers.

Concerning to the socio-cultural and economic context of farmers, Lio and Liu (2006) showed that the effects of ICT applications on

Table 6
Evaluation of reported rations on different farms compared to different suggested rations from the fodjan ration formulation “app.”

Variables	Reported ration	fodjan suggested rations			
		greater milk yield	healthier	cheaper	healthier and cheaper
Farm A (parity = 1)					
Feed intake, kg dry matter/cow/d					
Napier grass	8.1	8.0	8.5	8.9	8.5
Natural grass	3.2	3.6	3.6	3.6	3.6
Dairy meal (Pasho*)	3.0	2.9	2.3	2.0	2.4
Reported milk yield, kg/cow/d#	10.0	–	–	–	–
Predicted milk yield, kg/cow/d§	9.4	9.6	9.4	9.3	9.4
Feeding cost, KSh/kg milk	27.6	26.6	27.2	25.6	26.1
Farm B (parity = 2)					
Feed intake, kg dry matter/cow/d					
Maize silage	3.8	4.0	4.2	4.0	4.0
Rhodes grass hay	4.0	3.6	3.6	3.6	3.6
Fresh lucerne	0.9	0.8	0.8	0.8	0.8
Maize germ	1.9	2.3	2.5	2.3	2.3
Dairy meal (Pembe*)	1.9	1.9	1.4	1.9	2.1
Reported milk yield, kg/cow//d#	8.0	–	–	–	–
Predicted milk yield, kg/cow//d§	6.2	6.6	6.0	6.6	6.6
Feeding cost, KSh/kg milk	59.9	55.1	58.4	55.1	55.1
Farm C (parity = ≥ 3)					
Feed intake, kg dry matter/cow/d					
Fodder mix	8.5	8.6	none	7.7	8.6
Dairy meal (Alliance*)	1.8	1.8	none	2.4	1.8
Reported milk yield, kg/cow//d#	9.0	–	–	–	–
Predicted milk yield, kg/cow//d§	3.8	3.9	none	3.9	3.9
Feeding cost, KSh/kg milk	105.0	102.2	none	99.4	102.2

*Brand name for different Kenyan dairy meal producers; #milk yield reported on-farm by farmer for the ration on offer; §milk yield expected based on the optimized ration suggested by the fodjan “app”.
KSh: Kenyan Shillings obtained from local Kenyan markets, 108 KSh was (22.08.2020) equivalent to 1 USD (https://www.xe.com/currencyconverter/convert/?Amount = 1&From = USD&To = KES);

agricultural production are twice as high in developed countries than in developing countries. These findings may be explained by a lack of complementary ICT infrastructures such as internet connectivity, reliable electricity, and ICT literacy (Baumüller, 2018). Prevailing structural barriers such as weak markets, limited access to finance, and poor infrastructure also hamper the full potential of ICT applications (Lio and Liu, 2006) Such structural barriers cannot be fully addressed by ICT applications, but they need to be addressed holistically. This resonates with Mayberry et al. (2017), who argued that “packages of interventions are required to bridge [milk yield] gaps rather than single interventions.” For example, farmers may not be willing to produce more when there is a weak market or high risk of milk losses via spoilage. Consequently, interventions to close dairy cattle milk yield gaps must go beyond production to ensure that the supporting economic infrastructure is provided.

Finally, it is crucial to think about the business models behind ICT applications. Business models refer to the “fundamental questions every manager must ask: How do we make money in this business?” (Ovans, 2015, para. 8). Private investors would only provide ICT applications that enable them earn profits in the long-term. ICT applications without viable business models often fail to develop further and scale up but end up abandoned. According to a report on ICT applications in Africa, “the vast majority of businesses still rely on donor funding” as “farmers are unlikely to pay for (…) services” (CTA, 2019). Consequently, only few ICT applications in developing countries have scaled up (Deichmann et al., 2016) Depending on the entry points outlined above and the nature of the ICT applications provided, business models can be designed around different actors (Birner et al., 2021; Daum et al., 2021). In some business models, farmers pay for ICT applications, by subscribing on a pay-per-use or daily, monthly or yearly basis. Alternatively, input or service providers in the agricultural value chain could offer ICT applications for free to farmers as with the perspective of securing other benefits (Birner et al., 2021). For example, input companies may adopt business models that provide free services to farmers in return for collecting farmers’ data or advertising their products. For example, an animal feed company may offer an ICT application for general farm management including rations formulation, through which they can collect data on feeding practices, and market their products. Some entry points (e.g., traceability systems using radio-frequency identification to ensure animal feed quality) may be unattractive for private companies because they have public good characters (Birner et al., 2021), creating the need for cooperatives or governments to come in.

5. Conclusion

ICT applications could help address some existing biophysical and socio-economic constraints fostering milk yield gaps, including data collection for breeding programs, feeding management advice, and facilitating access to markets and capital. The case study in the present study revealed that 2 % to 6 % of the milk yield gap between the economic dairy cattle farm and the average dairy cattle farm in central rural Kenya could be closed albeit the limited variety of feed resources considered. Several factors could further explain the actual contribution of selected ICT applications to reduce existing milk yield gaps, including the quality of the models and data used in ICT applications, as well as more structural constraints that cannot be addressed by digital tools. To harness the full potential of ICT applications for closing milk yield gaps of dairy cattle in SSA, holistic approaches that use ICT applications as one solution alongside others, to address biophysical and socio-economic constraints, as well as structural barriers, must be employed.

CRediT authorship contribution statement

Christian Adjogo Bateki: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Thomas Daum:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Ana Salvatierra-Rojas:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Joachim Müller:** Supervision, Project administration, Funding acquisition. **Regina Birner:** Supervision, Project administration, Funding acquisition. **Uta Dickhoefer:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

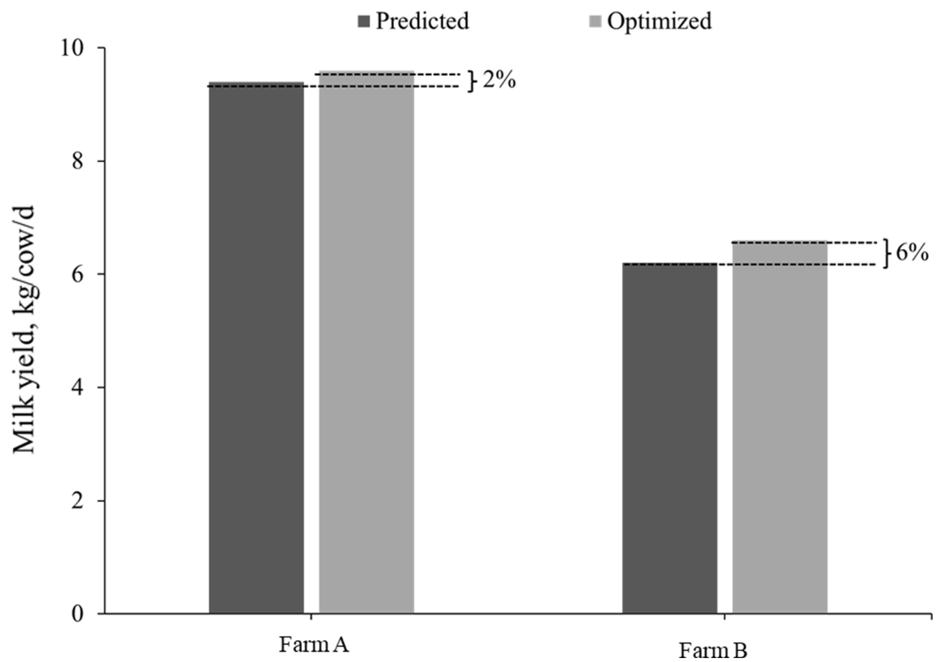

Fig. 3. Contrast of predicted and optimized milk yield from cows on farm A and B in Western and Central Kenya.

the work reported in this paper.

Acknowledgments

We are grateful for the financial support from the "Program of Accompanying Research for Agricultural Innovation" (PARI), which is funded by the German Federal Ministry of Economic Cooperation and Development (BMZ).

References

Abeygunawardena, H., Dematawewa, C.M.B., 2004. Pre-pubertal and postpartum anestrus in tropical Zebu cattle. Animal Reproduction Sci. 82–83, 373–387. https://doi.org/10.1016/j.anireprosci.2004.05.006.

Ainslie, A., 2013. The socio-cultural contexts and meanings associated with livestock keeping in rural South Africa. African J. Range Forage Sci. 30 (1-2), 35–38. https://doi.org/10.2989/10220119.2013.770066.

Aker, J.C., Ghosh, I., Burrell, J., 2016. The promise (and pitfalls) of ICT for agriculture initiatives. Agric. Econ. (United Kingdom) 47, 35–48. https://doi.org/10.1111/agec.12301.

Awa, D.N., Achukwi, M.D., 2010. Livestock pathology in the central African region: some epidemiological considerations and control strategies. Animal health research reviews/Conference of Research Workers in Animal Diseases 11 (2), 235–244. https://doi.org/10.1017/S1466252309990077.

Bateki, C., Van Dijk, S., Wilkes, A., Dickhoefer, U., White, R., 2020. Meta-analysis of the effects of on-farm management strategies on milk yields of dairy cattle on smallholder farms in the Tropics. Animal 1–9. https://doi.org/10.1017/S1751731120001548.

Bateki, C.A., Cadisch, G., Dickhoefer, U., 2019. Modelling sustainable intensification of grassland-based ruminant production systems: A review. Global Food Security 23, 85–92.

Bateki, C., Dickhoefer, U., 2018. A Diet Formulation "App" For Small-Medium Scale Dairy Cattle Farmers In The (Sub-)Tropics. Stuttgart, Germany.

Baumüller, H., 2018. The Little We Know: An Exploratory Literature Review on the Utility of Mobile Phone-Enabled Services for Smallholder Farmers. J. Int. Dev. 30 (1), 134–154. https://doi.org/10.1002/jid.v30.110.1002/jid.3314.

Bebe, B.O., Udo, H.M.J., Rowlands, G.J., Thorpe, W., 2003. Smallholder dairy systems in the Kenya highlands: Cattle population dynamics under increasing intensification. Livestock Production Sci. 82 (2-3), 211–221. https://doi.org/10.1016/S0301-6226(03)00013-7.

Beddow, J.M., Hurley, T.M., Pardey, P.G., Alston, J.M., 2015. Rethinking yield gaps. University of Minnesota, Minnesota - USA.

Birner, R., Daum, T., Pray, C., 2021. Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. Appl. Econ. Perspectives Policy.

Bwire, J.M.N., Wiktorsson, H., 2003. Effect of supplementary feeding strategies on the performance of stall-fed dual-purpose dairy cows fed grass hay-based diets. Asian-Australasian J. Animal Sci. 16 (3), 359–367. https://doi.org/10.5713/ajas.2003.359.

Cochran, W.G., Cox, G.M., 1992. Experimental Designs. Wiley.

CTA, 2019. The Digitalization of African Agriculture Report. Technical Center for Agriculture and Rural Cooperation (CTA).

Daum, T., Ravichandran, T., Kariuki, J., Chagunda, M., Birner, R. (2021). Connected cows and cyber chickens? Stocktaking and case studies of digital livestock tools in Kenya and India. Hohenheim Working Papers on Social and Institutional Change in Agricultural Development. 008-2021. University of Hohenheim.

Daum, T., 2018. We need more than apps. In: Development, R.-T.I.J.f.R. (Ed.), Rural-Urban Linkages. Synergies, Threats and Limitations. DLG-Verlag GmbH, Frankfurt - Germany. https://www.rural21.com/english/current-issue/detail/article/we-need-more-than-apps-00003058/.

Deichmann, U., Goyal, A., Mishra, D., 2016. Will digital technologies transform agriculture in developing countries? Agric. Econ. (United Kingdom) 47, 21–33. https://doi.org/10.1111/agec.12300.

Delgado, C.L., 2003. Rising Consumption of Meat and Milk in Developing Countries Has Created a New Food Revolution. J. Nutrit. 133, 3907S–3910S.

Delgado, C.L., Rosegrant, M.W., Steinfeld, H., Ehui, S.K., Courbois, C., 1999. Livestock to 2020: The Next Food Revolution. International Food Policy Research Institute Food, Agriculture, and the Environment Discussion Paper 28, Washington D.C. - USA.

Doldt, J., 2019. Evaluation and validation of a feed app for dairy farmers in Kenya (Master thesis). Hans-Ruthenberg-Institute of. In: Agricultural Science in the Tropics. University of Hohenheim, Stuttgart, Germany.

Duguma, B., Janssens, G.P.J., 2016. Assessment of feed resources, feeding practices and coping strategies to feed scarcity by smallholder urban dairy producers in Jimma town. Ethiopia. SpringerPlus 5, 717 (10.1186/s40064-016-2417-9).

Duncan, A.J., Teufel, N., Mekonnen, K., Singh, V.K., Bitew, A., Gebremedhin, B., 2013. Dairy intensification in developing countries: Effects of market quality on farm-level feeding and breeding practices. Animal 7 (12), 2054–2062. https://doi.org/10.1017/S1751731113001602.

FAO, 2000. Bridging the Rice Yield Gap in the Asia-Pacific Region. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand.

FAO, 2014. Impact of mastitis in small scale dairy production systems. Animal Production and Health Working Paper. No. 13, Rome.

FAO, DWFI, 2015. Yield gap analysis of field crops: Methods and case studies. Food and Agriculture Organization of the United Nations, Rome, Italy.

Faverdin, P., Baratte, C., Delagarde, R., Peyraud, J.L., 2011. GrazeIn: A model of herbage intake and milk production for grazing dairy cows. 1. Prediction of intake capacity, voluntary intake and milk production during lactation. Grass Forage Sci. 66, 29–44. https://doi.org/10.1111/j.1365-2494.2010.00776.x.

Fischer, R.A., Byerlee, D., Edmeades, G.O., 2009. Can technology deliver on the yield challenge to 2050? Accessed, http://www.fao.org/3/a-ak977e.pdf.

Gomez, K.A., Herdt, R.W., Barker, R., de Datta, S.K., 1979. A methodology for identifying constraints to high rice yields on farmers' fields. In: Farm-level Constraints to High Rice Yields in Asia. International Rice Research Institute, Los Baños, Philippines, pp. 1974–1977.

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A., 2011. Global Food Losses and Food Waste. FAO, Rome, Italy.

Henderson, B., Godde, C., Medina-Hidalgo, D., van Wijk, M., Silvestri, S., Douxchamps, S., Stephenson, E., Power, B., Rigolot, C., Cacho, O., Herrero, M., 2016. Closing system-wide yield gaps to increase food production and mitigate GHGs among mixed crop-livestock smallholders in Sub-Saharan Africa. Agric. Syst. 143, 106–113. https://doi.org/10.1016/j.agsy.2015.12.006.

Herrero, M., Di Mayberry, D., van de Steeg, J., Phelan, D., Ash, A., Diyezee, K., Robinson, T., Henderson, B., Gilbert, M., van Wijk, M., Godde, C., Blummel, M., Prestwidge, D., Stephenson, E., Power, B., Parsons, D., 2016. Understanding livestock yield gaps for poverty alleviation, food security and the environment. The LivesGAPS project - final report. Brisbane: CSIRO., Brisbane - Australia.
Jenet, A., Yimegnuhal, A., Fernandez-Rivera, S., Tegegne, A., Osuji, P.O., McCrabb, G., Kreuzer, M., 2004. Long-term response to feeding level in lactational performance of Boran (Bos indicus) and Boran X Holstein cows. Anim. Sci. 78, 331–343.
Kahumbu, S., 2012. Track your cow's development. In: Update, I. (Ed.), ICT innovation. CTA, Wageningen -, The Netherlands.
Kiambi, D., 2018. The use of Information Communication and Technology in advancement of African agriculture. Afr. J. Agric. Res. 13 (39), 2025–2036.
Lio, M., Liu, M.C., 2006. ICT and agricultural productivity: Evidence from cross-country data. Agric. Econ. 34, 221–228. https://doi.org/10.1111/j.1574-0864.2006.00120.x.
Little, W., Collis, K., Gleed, P., Sansom, B., Allen, W., Quick, A., 1980. Effect of reduced water intake by lactating dairy cows on behaviour, milk yield and blood composition. Vet. Rec. 106 (26), 547–551. https://doi.org/10.1136/vr.106.26.547.
Maleko, D., Msalya, G., Mwilawa, A., Pasape, L., Mtei, K., 2018. Smallholder dairy cattle feeding technologies and practices in Tanzania: failures, successes, challenges and prospects for sustainability. Int. J. Agricultural Sustainability 16 (2), 201–213. https://doi.org/10.1080/14735903.2018.1440474.
Mayberry, D., Ash, A., Prestwidge, D., Godde, C.M., Henderson, B., Duncan, A., Blummel, M., Ramana Reddy, Y., Herrero, M., 2017. Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India. Agric. Syst. 155, 43–51. https://doi.org/10.1016/j.agsy.2017.04.007.
McGill, D.M., Thomson, P.C., Mulder, H.A., Lievaart, J.J., 2014. Strategic test-day recording regimes to estimate lactation yield in tropical dairy animals. Genet. Select. Evol. 46 (1), 1–13.
Meyer, S.J., Hubbard, K.G., Wilhite, D.A., 1989. Estimating potential evapotranspiration: the effect of random and systematic errors. Agric. For. Meteorol. 46 (4), 285–296.
Mockshell, J., Ilukor, J., Birner, R., 2014. Providing animal health services to the poor in Northern Ghana: rethinking the role of community animal health workers? Trop. Anim. Health Prod. 46 (2), 475–480. https://doi.org/10.1007/s11250-013-0518-9.
Moyo, J.M., Bah, E.H.M., Verdier-Chouchane, A., 2015. Transforming Africa's agriculture to improve competitiveness. World Economic Forum, World Bank and AfDB (2015). The Africa competitiveness report 2015. Geneva: WEF.
Ngongoni, N.T., Mapiye, C., Mwale, M., Mupeta, B., 2006. Factors affecting milk production in the smallholder dairy sector of Zimbabwe. Livestock Research Rural Dev. 18 (5), 1–21.
Onyango, A.A., Dickhoefer, U., Rufino, M.C., Butterbach-Bahl, K., Goopy, J.P., 2019. Temporal and spatial variability in the nutritive value of pasture vegetation and supplement feedstuffs for domestic ruminants in Western Kenya. Asian-Australasian J. Animal Sci. 32 (5), 637–647.
Ovans, A. (2015). What Is a Business Model? Harvard Business Review. Retrieved from https://hbr.org/2015/01/what-is-a-business-model (23/08/2021).
Owen, E., Smith, T., Makkar, H., 2012. Successes and failures with animal nutrition practices and technologies in developing countries: A synthesis of an FAO e-conference. Anim. Feed Sci. Technol. 174 (3-4), 211–226. https://doi.org/10.1016/j.anifeedsci.2012.03.010.
Place, F., Ralph, R., Maina, L., Steven, F., Sinja, J., Wanjiku, J., 2009. The impact of fodder trees on milk production and income among smallholder dairy farmers in East Africa and the role of research. ICRAF Occasional Paper No. 12. World Agroforestry Centre, Nairobi - Kenya.
Pingali, P.L., Heisey, P.W., 2001. Cereal-crop productivity in developing countries: Past trents and future prospects. In: Alston, J.M., Pardey, P.G., Taylor, M.J. (Eds.), Agricultural Science Policy: Changing Global Agendas. International Food Policy Research Institute, Washingtion, D.C.
Rockström, J., Falkenmark, M., 2000. Semiarid crop production from a hydrological perspective: Gap between potential and actual yields. Crit. Rev. Plant Sci. 19 (4), 319–346. https://doi.org/10.1080/07352680091139259.
Roetter, R., Aggarwal, P.K., Tan, P.S., Hoanh, C.T., Cabrera, J.M.C.A., Nunez, B., 1998. Use of crop simulation models and alternative yield estimation techniques for optimizing agricultural land use and resource management. In: Roetter et al. Exchange of Methodologies in Land Use Planning: Proceedings of an International Workshop Held at Can Tho, Vietnam. International Rice Research Institute. Volume 1. Issue 1 of SysNet research paper series, Los Banos - Philippines, pp. 15-29.
Salvatierra-Rojas, A., Torres-Toledo, V., Mrabet, F., Müller, J., 2018. Improving milk value chains through solar milk cooling. ZEF Working Paper 172. Center for Development Research. University of Bonn -, Germany.
Snyder, K.A., Miththapala, S., Sommer, R., Braslow, J., 2017. The yield gap: Closing the gap by widening the approach. Exp. Agric. 53 (3), 445–459. https://doi.org/10.1017/S0014479716000508.
Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 143, 76–90. https://doi.org/10.1016/j.fcr.2012.10.007.
Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance-A review. Field Crops Res. 143, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009.
Verdier-Chouchane, A., Karagueuzian, C., 2016. Moving Towards a Green Productive Agriculture in Africa: The Role of ICTs. Africa Economic Brief, 7(7). Côte d'Ivoire: African Development Bank.
White, R.R., Capper, J.L., 2014. Precision diet formulation to improve performance and profitability across various climates: Modeling the implications of increasing the formulation frequency of dairy cattle diets. J. Dairy Sci. 97 (3), 1563–1577. https://doi.org/10.3168/jds.2013-6859.
Žgajnar, J., Juvančič, L., Kavčič, S., 2009. Combination of linear and weighted goal programming with penalty function in optimisation of a daily dairy cow ration. Agric. Econ. 55 (No. 10), 492–500.