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World Potassium Use Efficiency in Cereal Crops

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ABSTRACT

Worldwide potassium (K) fertilizer use has grown, while the expected fertilizer use efficiency has decreased. The objective of this paper was to estimate potassium use efficiency (KUE) for cereal crops and report on methods that will most likely lead to improved KUE. World KUE was calculated using the total area under cereal production, total cereal grain production, percent K content in cereal grains and K fertilizer consumed from 1961 to 2015. All data was obtained from FAOSTAT except percent K grain content, which was acquired from the USDA. The reported KUE estimate included assumptions established in prior literature. The percent K coming from the soil was estimated at 71%, while previous year K fertilizer-residual-effects were offset by knowing that similar amounts of fertilizer K will be applied in following years. At current consumption rates, existing K reserves as K_20 are estimated to last 100 yr meaning that mining operations will need to expand to meet expected market demands. Results showed that cereal production increased by a factor of 3.2 from 1961 to 2015 and that was accompanied by a threefold increase in fertilizer K consumed. Estimated KUE from 1961 to 2015 for world cereal crops using the difference method was 19%. Combined with findings from this paper, estimates of N, P, and K use efficiency for cereal production in the world stand at 33, 16, and 19%, respectively.

Core Ideas

- Potassium use efficiency in cereals is unknown.
- World demand for potassium in agriculture is increasing.
- Potassium is a non-renewable resource.

The three most commonly required and widely used nutrients in agriculture are nitrogen (N), phosphorus (P), and K. With a growing world population, food security has become increasingly more important. In addition, duration and incidences of drought and heat stress have been predicted to increase which would adversely affect major crops and food security (Zörb et al., 2014). Food production for an increased world population will require alternative technologies that will increase the yield per unit land. Increased production per unit area will require a greater need for commercial fertilizers (Stewart et al., 2005). Consequently, a constant supply of N, P and K is needed for increasing food production to meet growing world food demands. Nonetheless, higher inputs of N and P fertilizers have resulted in an imbalance between N, P and K in plant and soil systems (Dobermann et al., 1996; Smil, 1999; Pathak et al., 2003; Fan et al., 2005; Römheld and Kirkby, 2010; Yadav and Sidhu, 2016).

It is estimated that between 2.1 to 2.3% of the earth's crust is K that making it the seventh most abundant element (Schroeder, 1978; Wedepohl, 1995; Havlin et al., 2005; Zörb et al., 2014). Soil K concentration for mineral soils varies widely between 0.04 and 3.0% (Sparks, 1987). The K contribution from various rocks include igneous rocks such as granites and syenites (46–54 g K kg^{-1}), basalts (7 g K kg^{-1}), and periodotites (2 g K kg^{-1}), sedimentary rocks like clayey shales (30 g K kg^{-1}), and limestone have an average of only 6 g K kg^{-1} (Malavolta, 1985). It is estimated that 3.7 billion tons of K as a K_2O equivalent are left in reserves worldwide, while resource estimates are around 250 billion tons (Jasinski, 2016). Canada is the largest producer with 35% of total world production (Roberts and Stewart, 2002). As per the USGS report (Jasinski, 2016), Canada, Belarus, and Russia have reserves of 1, 0.75, and 0.6 billion tons, respectively.

Most of the K in soil is not plant available and can be categorized into four pools: soil solution K, exchangeable K, non-exchangeable K, and structural K (Syers, 2003; Moody and Bell, 2006). Growing plants assimilate K from the soil solution. Exchangeable K can quickly be released from soil particles and enter the soil solution, however, releasing K from the other two forms takes more time and will not be as readily available. The fraction of plant available K in soil solution is 0.1 to 0.2% of total soil K, exchangeable K is 1 to 2%, non-exchangeable K is 1 to 2% (fixed in 2:1 clays), and the soil-unavailable K is 96 to 99%

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Abbreviations: KUE, potassium use efficiency; PUE, phosphorus use efficiency.

(Sparks 1987; Wang et al., 2010; Britzke et al., 2012; Sardans and Peñuelas, 2015). Work by Syers (2003), Römheld and Kirkby (2010), and Yadav and Sidhu (2016) illustrate detailed cycles of K in soils. The K availability varies with soil types and is mainly affected by physical (the type and amount of clay and organic matter), chemical, and biological properties of the soil. Also, K in soils is influenced by the nature of the actual parent material, degree of weathering, addition of manures and fertilizers, leaching, erosion, and crop removal.

Soils around the globe are often found to be K deficient. One-fourth of arable soils and three-fourths of paddy soils are deficient in K in China (Rengel and Damon, 2008; Römheld and Kirkby, 2010). Similar trends were noted for wheat production in southwestern Australia, where K deficiencies have also increased (Rengel and Damon, 2008; Römheld and Kirkby, 2010). Yadav and Sidhu (2016) noted that 72% of agricultural soils in India require immediate K fertilization for improved crop production. The soils where K deficiency predominantly occurs are acid sandy soils, waterlogged soils, and saline soils (Mengel and Kirkby, 2001).

One of the main reasons for K deficiency is biomass removal from the soil in the form of grain, straw, or hay (Smil, 1999). Leaching and erosion of K also contribute toward reduced soil K content (Rengel and Damon 2008). Dobermann (2007) deduced that K fertilizer use has declined in recent years leading to deficient soils, as K removed is not adequately replaced. Smil (1999) documented that K fertilizers are applied only to replenish 35% of the K removed. Additionally, Manning (2015) reported that K mining from soil far exceeds the counterbalancing inputs, typically less than 10% of K removal.

Potassium is the most abundant cation in plants and plays an important role in agricultural production systems. Potassium has been noted to assist with resistance against pests and diseases, photosynthesis, osmoregulation, enzyme activation, protein synthesis, ion homoeostasis and stability between monovalent and divalent cations (Bhandal and Malik, 1988; Zhao et al., 2001; Mengel and Kirkby, 2001; Brar and Tiwari, 2004; Kanai et al., 2007; Amtmann et al., 2008). In addition, K helps with plant turgor, stress tolerance, enzyme stimulation in crops, and is needed for crop growth and development (Marschner, 2011; Zörb et al., 2014). Furthermore, K fertilization could improve N and P use efficiency, as well as productivity and quality of agriculture production (Epstein and Bloom, 2005). Additional comprehensive information on K in plants is presented in (Römheld and Kirkby, 2010; Zörb et al., 2014) and textbooks on plant nutrition (Marschner 2011; Mengel and Kirkby, 2001; Epstein and Bloom 2005).

The major form of K fertilizer that is used is potassium chloride (KCl), it is a natural mineral mined from deep deposits. Other commercially available sources include potassium sulfate and potassium nitrate, which are side products from KCl mining (Zörb et al., 2014). Typically, one application is sufficient as K is adsorbed to clay minerals; however, in light textured soils it is efficient to have two to three split applications (Annadurai et al., 2000). Niu et al. (2013) noted increased yields and further improvement in N and P use efficiency with K fertilization. The yield response to K depends on N and P nutrition, and this interaction is normally positive (Bruns and Ebellhar, 2006; Wang et al., 2007; Duncan et al., 2018)

Cakmak and Schjoerring (2008) noted that despite the importance of K in crop production there has been little published work on K. The world N use efficiency for cereal crops was determined to be 33% (Raun and Johnson, 1999) while that for P was 16% (Dhillon et al., 2017). Nonetheless, similar estimates for K in cereal crops have not been published. Nutrient use efficiency is important for all elements so as to delineate a point of reference for future improvement. The objective of this work was to calculate the global KUE for cereal crops, using methods used to estimate N and P use efficiencies.

MATERIALS AND METHODS

World values were derived over a 55-yr period that included harvested area (ha), area under cereal production (ha), cereal production quantity (Mg), and fertilizer K consumption (Mg) using the FAOSTAT database (FAO, 2016). Cereal crops for this study included maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), barley (*Hordeum vulgare* L.), millet (*Pennisetum glacum* L.), oats (*Avena sativa* L.), rye (*Secale cereale* L.), triticale (*Triticale hexaploide* L.) and “other cereal crops”. These other cereal crops were canary seeds (*Phalaris canariensis*), buckwheat (*Fagopyrum esculentum* Moench), fonio (*Digitaria exilis* stapf), mixed grains, and quinoa (*Chenopodium quinoa*). Even though K availability from manure is 100% (Eghball et al., 2002) due to inaccessible manure consumption data globally, the KUE was only calculated for inorganic fertilizer K inputs.

This work used world-statistics available from FAOSTAT and used similar methods reported by Raun and Johnson (1999) and Dhillon et al. (2017). This methodology embodied the relationship between fertilizer consumed by cereal crops and the amount of K removed in the grain. To determine global KUE for cereal crops, the difference method was used as in the following equation:

$$\text{KUE} = \frac{\text{K uptake in cereal grain} - \text{K removed from soil}}{\text{K applied as fertilizer to cereal crops}} \times 100$$

Potassium fertilizer consumption in cereal crops was calculated based on the ratio of harvested area under cereal crop production as compared to the total world harvested area. The fraction of total world harvest area, specifically under cereal production, was multiplied by the total K fertilizer consumption, to obtain K fertilizer used in cereal crops. Cereal grain K uptake was calculated using crop specific grain K content obtained from the USDA Plants Database (USDA, 2016). Cereal grain K uptake (Mg) was calculated by multiplying the crop specific grain K content, by the production quantity of that given crop. An average grain K content was used for “other cereal crops”. Potassium removed from the soil was calculated based on the average fertilizer recovery reported in Table 1. To calculate K removed from the soil, cereal grain K uptake was multiplied by 71%. This value from the soil was based on average KUE of 29% based on estimates for agronomic KUE and internal KUE reported in literature for maize, rice and wheat and further delineated in Table 1.

The sum of total area and production for different countries for each year was calculated for each crop. These were further used to calculate average area and production of each cereal. The *summary* and *means* procedures in SAS 9.4 (SAS Institute, 2011) were used to calculate descriptive statistics.

Table 1. Published studies reporting K fertilizer recovery in cereal crops.

Crop	Description	Reported agronomic K efficiency†	Reported recovery K efficiency‡	Reference
		%		
Wheat	K rates of 51, 102, and 154 (kg ha^{-1})	6.1, 5.9, 3.1	23.7, 19.0, 13.3	(Zhan et al., 2016)
Wheat	5-yr experiment	5.4	50.5, 55.0, 41.8, 36.4	(Zhang et al., 2011)
Maize	5-yr experiment	8.0	54.2, 90.9, 63.5, 53.7	(Zhang et al., 2011)
Rice	10 long-term fertility experiments with irrigated rice	9.9, 26, 0.0, 4.5, 0.0, 2.9, 3.2, 0.0, 18.3, 18.2	37, 61, 59, 42, 68, 57, 76, 89, 61, 56	(Dobermann et al., 1996)
Maize	16-yr average at 133 and 225 kg K_2O ha^{-1}	10.8, 4.90	37.3, 28.5	(Qiu et al., 2014)
Rice	5-yr experiment without residue retention	12.5, 9.30, 7.70	62, 54, 42	(Singh et al., 2018)
Rice	5-yr experiment with residue retention	6.3, 4.8, 3.5	45, 46, 44	(Singh et al., 2018)
Maize	5-yr experiment without residue retention	13.8, 11.0, 9.00	51, 48, 52	(Singh et al., 2018)
Maize	5-yr experiment with residue retention	8.6, 7.1, 5.7	42, 38, 43	(Singh et al., 2018)
Average		7.81	50.58	
Overall average		29.19		

† Agronomic K use efficiency (%) computed as: (grain yield in plot that received K fertilizer – control in which no K fertilizer was applied)/(fertilizer K input).
‡ Recovery K use efficiency (%) computed as: (grain yield)/(K uptake).

RESULTS AND DISCUSSION

The amount of K that remains globally is finite and is estimated to be near 3.7 billion tons as K_2O reserves and 250 billion tons as resources (Jasinski, 2016). The reported potash usage was projected to increase gradually from 35.5 to 39.5 million tons K_2O in 2019, with Asia and South America accounting for most of this consumption increase (Jasinski, 2016). The average worldwide consumption of K as K_20 in the last 5 yr (2011 to 2015) was 37 million tons (FAO, 2016). At that consumption rate, K_20 reserves are estimated to last for 100 yr. Manning (2015), reported a decrease in the projected life of potash availability from 350 to 175 yr due to lower reserves reported in 2013 (Jasinski, 2014).

In the past 55 yr, world cereal production has increased by a factor of 3.2 whereas area under cereal production has increased only 1.1-fold from 1961 to 2015 (Fig. 1). This production increase was supplemented by a 3-fold increase in fertilizer K (Fig. 2). Since 1961, wheat area has increased by a factor of 1.1; alternatively, wheat production has more than tripled (3.3-fold) (Fig. 3). The area under cultivated maize has increased 1.7-fold while production has increased by a factor of 4.9 from 1961 to 2015 (Fig. 4). Similarly, the area under cultivated rice increased by a factor of 1.4, with production showing a 3.4-fold increase since 1961 (Fig. 5). It has been estimated that 28 to 79% of yield improvement was attributed to breeding and 21 to 48% was attributed to improved nutrient usage (Bell et al., 1995; Nalley et al., 2009). Many scholars have noted a significant cereal yield increase and found the reason to be changes in agricultural practices, increased fertilizer and pesticide use, and an increase in irrigation (Borlaug, 1983; Khush, 1999; Reynolds et al., 1999; Hafner, 2003; Battenfield et al., 2013).

The KUE values over the last 55 yr are highly variable (Fig. 6). The maximum agronomic KUE obtained was 26% and it was found in the years 1993, 1996, and 2000 (Fig. 6). Lower KUE levels of 15% were found from 1975 to 1980. On average for all 55 yr (1961 to 2015), KUE was found to be 19% (Table 2). The changes in KUE values were closely related to the quantity of fertilizer used, when higher amounts of fertilizer were used, KUE values were found to be lower. The changes in KUE followed a very similar trend reported by Dhillon et al. (2017) for phosphorus use efficiency (PUE). Lower PUE values were obtained in 1980 and 1988, alternatively, the higher PUE values were noted in years 2008 and 2009. The similar trends represent consistency in macro nutrient sales (N, P, and K), which was the same for both P and K (FAO, 2016).

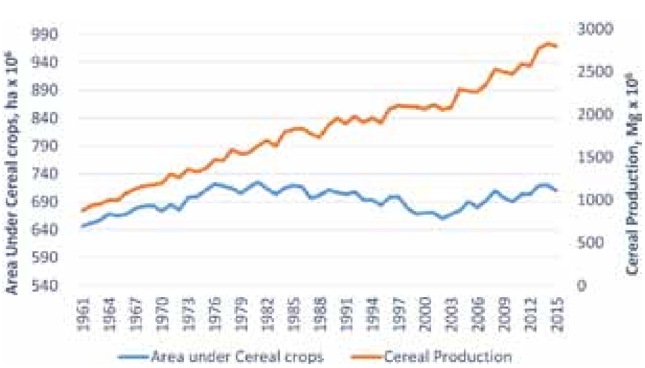

Fig. 1. Worldwide cereal area and production from 1961 to 2015.

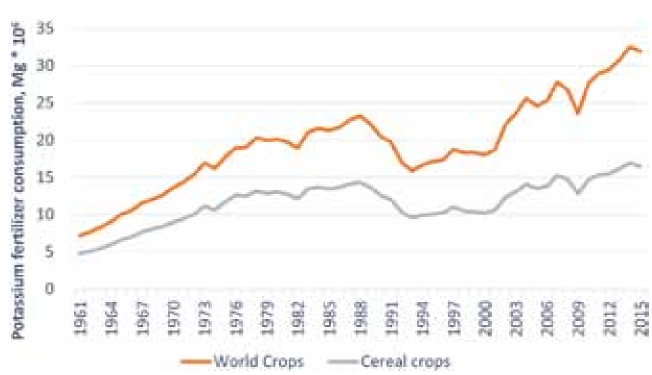

Fig. 2. Fertilizer K consumption for world crops and cereal crops from 1961 to 2015.

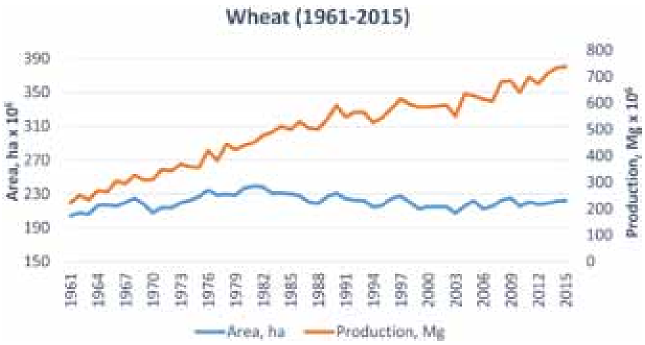

Fig. 3. Worldwide wheat area and production from 1961 to 2015.

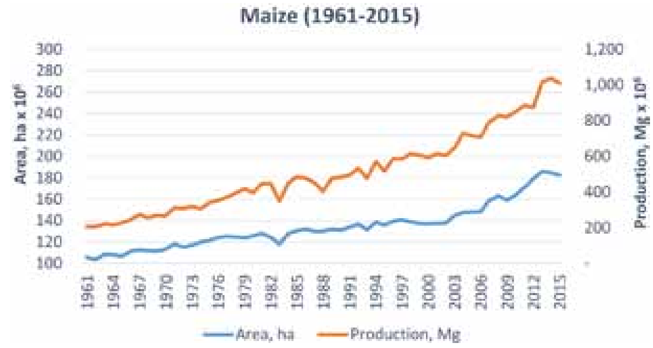

Fig. 4. Worldwide maize area and production from 1961 to 2015.

Strategies to Improve Potassium Use Efficiency

Numerous researchers have pointed out the inadequacy of soil extraction methods based on exchangeable K for making fertilizer recommendations (Dobermann et al., 1996; Prasad, 2009; Römheld and Kirkby, 2010). This is especially important on soils with 2:1 clays mainly because of the contribution of slowly available K (Hinsinger, 2002). However, soil extraction methods based on exchangeable K are successful in soil without 2:1 layer silicates (Mengel and Kirkby 2001). The release of non-exchangeable K in soils increases as the concentration of solution and exchangeable K decreases (Sarkar et al., 2013). Sarkar et al. (2013) further noted that Alfisols rich in kaolinite requires frequent K fertilization under long-term cropping compared to Entisols and Inceptisols dominant in illite. Thus, it is imperative to use the right soil extraction method when making fertilizer recommendations. The ability to accurately predict K availability and the specific crop potential to extract K from soil could significantly improve the accuracy of fertilizer recommendations and thus KUE. Furthermore, Römheld and Kirkby (2010) noted that the use of site-specific information regarding the amount and quality of K-bearing minerals and weather factors affecting root growth using GIS systems could improve the final fertilizer recommendation.

Changes to current farming practices will be a key to improving K use efficiency. In soils where high K fixation occurs, more capital investments are needed to build up K reserves within the soil (Dobermann, 2007). Those areas where lower fixation of soil K occurs, the focus must be on keeping a better balance between soil K levels and K removal rates in the crop (Dobermann, 2007). This is a well-known concept, but lower technology adoption occurs in the developing world due to financial stress (Cassman et al., 1989; Dobermann, 2007).

Improving K use efficiency requires a fundamental understanding of nutrient management. The potassium fertilizer industry strongly supports the method of applying the nutrient at the right rate, at the right time, and the right place as a way to obtain optimum efficiency (Roberts, 2008). Furthermore, increased adoption of no-tillage (NT) practices imposes reconsideration of fertilizer management based on an investigation in tilled soils (Duiker and Beegle, 2006). The distribution and availability of essential nutrients are different in NT compared to conventional tillage (CT) systems. With lower initial K fertility and low residue levels, banding K fertilizer has proven to have a yield advantage over surface-broadcast methods (Yibirin, 1993). Also, in areas receiving lower rainfall, maize yields can be increased with deeper placement of K (Bordoli and Mallarino, 1998).

Furthermore, increasing the mobility of K in the soil could improve its availability (Shin, 2014). Enrichment of beneficial microorganisms may also offer an improvement in K availability in soil (Shin, 2014; Yadav and Sidhu, 2016; Ahmad et al., 2016). Yadav and Sidhu (2016) noted that the secretion of organic acids like citric, oxalic and tartaric acids by K solubilizing microorganisms could improve K release from K-bearing minerals. They also noted K solubilizing microorganisms as a cost-effective and environmental-friendly way to improve K availability and thus KUE.

Leaching can be a cause of low KUE in coarse textured soils. One of the ways to improve KUE is via the use of split applications during the growing season which simultaneously reduces K loss due to leaching (Baligar and Bennett, 1986b; Kolar and Grewal, 1994; Römheld and Kirkby 2010). Split application of K increased rice yields by 14.5% in an experiment conducted to study the response of two high-yielding cultivars on silty clay loam soils (Pal et al., 2000). It was further noted that split applied K in

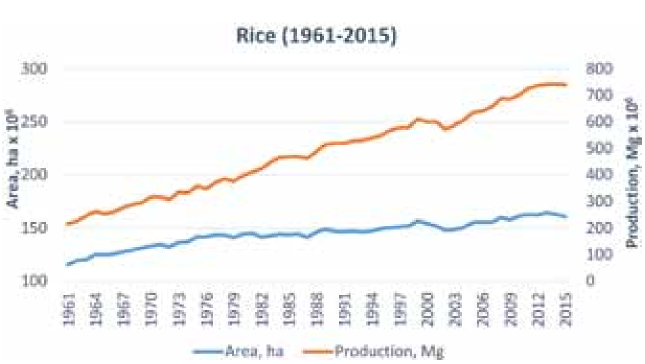

Fig. 5. Worldwide rice area and production from 1961 to 2015.

Fig. 6. Historical estimates of world potassium use efficiency (KUE) from 1961 to 2015 for cereal crops.

Table 2. World harvested area, consumption of K fertilizers for cereal production, K removed in grain and estimated potassium use efficiency (KUE) averaged over 55 yr (FAO, 2016).

Commodities and computations	Amount	Variable
World harvested area, ha		
Maize	134,001,535	
Rice	144,586,625	
Wheat	220,909,448	
Sorghum	45,333,785	
Barley	65,856,938	
Millet	38,125,892	
Oats	21,105,674	
Rye	14,687,598	
Triticale	1,950,278	
Other cereals	7,062,529	
Cereal harvested area	693,620,302	*A*
Total harvested area	1,147,570,987	*B*
World area under cereal production	60%	$C = (A/B)\times100$
World fertilizer K consumption, Mg		
Total	19,471,294	*D*
Cereal crops	11,682,776	$E = C\times D$
Production quantity, Mg		
Maize	510,661,922	
Rice	481,582,363	
Wheat	495,193,028	
Sorghum	59,851,529	
Barley	141,814,194	
Millet	28,107,717	
Oats	37,289,169	
Rye	25,570,189	
Triticale	6,971,478	
Other cereals	16,125,690	
Total world cereal production	1,803,167,279	*F*
World cereal grain K removal, Mg		
Maize	1,758,720	
Rice	2,182,531	
Wheat†	2,317,503	
Sorghum	231,446	
Barley‡	759,651	
Millet§	114,108	
Oats¶	164,855	
Rye	132,658	
Triticale	39,737	
Other cereals	73,906	
Total	7,775,117	*G*
Grain K uptake coming from soil#	5,505,560	*H*
Potassium use efficiency	19%	$[(G - H)/E]\times100$ = KUE

† Wheat: average of wheat-bread-hard-red-spring, wheat-bread-hard-red-winter, wheat-bread-soft-red winter, wheat-bread-soft-white winter, wheat Durum and wheat-spelled.

‡ Barley: average of 2 row crops, 6 row crops (excluding Pacific coast) and 6 row crops (Pacific coast only).

§ Millet: average of foxtail, pearl, and porso.

¶ Oat: average of Pacific coast only and excluding Pacific coast.

$H = G \times 0.708$ (based on 29.19% estimate of KUE reported in Table 1).

wheat could improve N uptake and increase grain yields (Lu et al., 2014). Additionally, foliar application of K has been found to improve grain yield and drought tolerance in wheat (Aown et al., 2012). When possible, placing nutrients on the leaves of plants can be an incredibly efficient method of application, in addition to providing disease control (Mann et al., 2004). It should be noted that foliar K is still somewhat controversial. Sandy soils are prone to K leaching resulting in low KUE in agriculture systems (Rengel and Damon, 2008). Liming acid soils can improve cation exchange capacity (CEC) and neutralize aluminum toxicity. This increase in CEC can be beneficial in reducing K leaching losses by reducing the soil solution concentration of K (Baligar and Bennett, 1986a).

Under excessive K supply and availability, K is prone to luxurious uptake, which leads to decreased KUE. Luxury consumption uptake does not result in yield gains. Zhan et al. (2016) reported that KUE was reduced from 19 to 13.3% when the K rate was increased from 102 to 154 kg ha^{-1}. Following local soil test recommendations has always afforded improved use efficiency, while avoiding over application. However, first and foremost, the value and need for soil testing must always be communicated. Applying optimum rates of K can also improve KUE. Moreover, recent studies have demonstrated that remote sensing (hyperspectral) could be used to accurately predict K content, which could be used for optimum K fertilizer application (Pimstein et al., 2011; Mahajan et al., 2014).

Another major reason for lower KUE is complete removal of crop residue. Close to 75 to 80% of K removed from the soil is retained in non-grain crop residues (Singh et al., 2018). Improved crop residue and organic waste management aids in avoiding K depletion (Bijay-Singh et al., 2004; Öborn et al., 2005). Furthermore, crop K requirements could be improved by retention of crop residue (Yadvinder-Singh et al., 2010; Singh et al., 2018) further improving KUE. Also, low KUE is encountered due to lower fertilizer consumption in Africa, which only consumes 1.5% of world potash fertilizer production (Manning, 2015). Mueller et al. (2012) noted that with a 35% increase in K fertilizer consumption, 73% underachieving areas in Sub-Saharan Africa could improve yields.

CONCLUSIONS

The objective of this study was to calculate KUE in cereal crops using previously published methods for NUE and PUE. Also, the lifespan of K reserves as $K_2 0$, at the current consumption rate is estimated at 100 yr meaning that mining operations will need to expand to other known deposits to keep up with growing demand. In the past 55 yr, cereal production has increased by a factor of 3.2, with a threefold increase in fertilizer K consumption. Using the difference method, KUE for cereal crop production in the world was estimated to be 19%. This study provides an estimated world value needed for comparison, and for future improvements in KUE. World cereal crop estimated KUE was 19% and that emphasizes the need to develop improved fertilization methods and production practices that further conserve this non-renewable natural resource. Estimates of N, P, and K use efficiency for world cereal production are reported at 33, 16, and 19%.

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CONFLICT OF INTEREST

The mention of any trademarked products or equipment utilized in this experiment was for research purposes only and does not act as an endorsement by Oklahoma State University. The authors and Oklahoma State University have no direct financial relation with any of the named manufacturers, thus the authors declare there is no conflict of interest regarding the publication of this manuscript.

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