



# Improving Nitrogen Use Efficiency—A Key for Sustainable Rice Production Systems

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Fertilizer use and genetic improvement of cereal crops contributed to increased yields and greater food security in the last six decades. For rice, however, fertilizer use has outpaced improvement in yield. Excess application of nutrients beyond crop needs, especially nitrogen (N), is associated with losses to the environment. Environmental pollution can be mitigated by addressing fertilizer overuse, improving N use efficiency, while maintaining or improving rice productivity and farmers' income. A promising approach is the site-specific nutrient management (SSNM), developed in the 1990s to optimize supply to meet demand of nutrients, initially for rice, but now extended to other crops. The SSNM approach has been further refined with the development of digital decision support tools such as Rice Crop Manager, Nutrient Expert, and RiceAdvice. This enables more farmers to benefit from SSNM recommendations. In this mini-review, we show how SSNM can foster sustainability in rice production systems through improved rice yields, profit, and N use efficiency while reducing N losses. Farmer adoption of SSNM, however, remains low. National policies and incentives, financial investments, and strengthened extension systems are needed to enhance scaling of SSNM-based decision support tools.

**Keywords:** precision nutrient management, sustainability, rice agri-food systems, digital tools, profitability

## INTRODUCTION

Optimal nutrient management in rice is important for food security, climate change mitigation, adaptation and transformation, and attainment of several sustainable development goals (Cakmak, 2002; Kanter et al., 2019; Lal et al., 2020). Fertilizer use has reduced agriculture expansion into natural ecosystems by increasing crop productivity on existing land. However, while yields increased with fertilizer use in the 1960s, they stagnated in intensive rice systems in the mid-1980s despite the development of varieties with greater yield potential (Dawe and Dobermann, 1999). This resulted in large yield gaps. This was largely due to excessive or imbalanced fertilizer use based on increased reliance on blanket fertilizer application, coupled with a rapid decline in the efficiency of fertilizer uptake by plants, indicating that increased fertilizer use outpaced yield improvements (Cassman and Pingali, 1995; Tilman et al., 2002). The orientation of producing more food, associated with fertilizer overuse, particularly nitrogen (N), has caused a deterioration in soil physical, chemical, and microbiological properties and functions and increased soil and water pollution (Pingali, 2012; Srivastava et al., 2020). With increasing pressure to meet global food demand while fostering environmental sustainability, a paradigm shift is needed to a more judicious use of N fertilizer.

About 50% of global N fertilizer is applied to major cereals: *Zea mays* (maize; 17%), *Triticum aestivum* (wheat; 18%), and *Oryza sativa* (rice; 16%) (Heffer et al., 2017). However, globally, N use efficiency, a measure of the short-term balance between N used for grain production and N lost to the environment, has remained below 40% (Omara et al., 2019), indicating that more than 60% of applied N remains unused or is lost from soil (Dobermann, 2000; Ladha et al., 2005). Increasing N use efficiency in rice agri-food systems becomes all the more important, given that the commodity is a staple food for more than half the global population (GRiSP, 2013). More than 90% of the rice is produced in Asia, mostly by smallholder farmers. Due to high subsidy on urea fertilizer, farmers tend to apply large quantities of N fertilizer in excess of plant requirements (Ladha et al., 2005). However, grain yield response diminishes as N fertilizer rate increases and may cause lodging and susceptibility to pest and disease damage when overapplied (Balasubramanian et al., 1998; Duy et al., 2004). Excess reactive N has detrimental effects in agroecosystems, such as nitrous oxide emissions, increased soil acidity, decreased biodiversity, and groundwater contamination (Galloway et al., 2003).

## Nitrogen Use Efficiency Trends in Rice Production Systems

In rice production, farmers apply large amounts of N fertilizer to maximize yield, but only 20–50% of N is taken up by the crop. N use efficiency remains low with a global average partial factor of productivity N (PFP N) of about 40 kg grain kg<sup>-1</sup> N applied (Figure 1). This is largely due to farmers applying large quantities of N fertilizer at early growth stages when the rice plants have not fully developed the root system. The resulting loss of the applied N, which is a mobile nutrient leads to increased water and land pollution and greenhouse gas (GHG) emissions (Shaviv and Mikkelsen, 1993; Xu et al., 2012; Zhang et al., 2013). Dobermann (2007) reviewed the commonly used N use efficiency indices in agronomy research, which include agronomy efficiency, recovery efficiency, internal efficiency, physiological efficiency, and PFP N. PFP N is commonly used in agronomy and is useful when comparing across different management practices and where there are no N omission plots to enable calculation of other indices (Dobermann, 2007). PFP N is an aggregate index which integrates indigenous N supply from the soil and that applied from external sources. It generally declines with increasing N application rates.

A PFP N of 60 kg grain kg<sup>-1</sup> N applied or greater indicates well-managed systems (Dobermann, 2005). PFP N has remained well below this threshold in many rice growing Asian countries compared to developed countries (Heffer et al., 2017). While PFP N increased between 2006 and 2014 in China, Indonesia, and Vietnam, it stagnated in India at 33 kg grain kg<sup>-1</sup> N (Figure 1). In contrast, in the Philippines, Thailand, Iran, and Pakistan, PFP N declined during the same period. It should be noted, however, that available data on fertilizer use by crop and country are unreliable. The contrasting PFPs could be due to management, e.g., the reduction in N fertilizer rate associated with the controls introduced in China (Chen et al., 2014) could

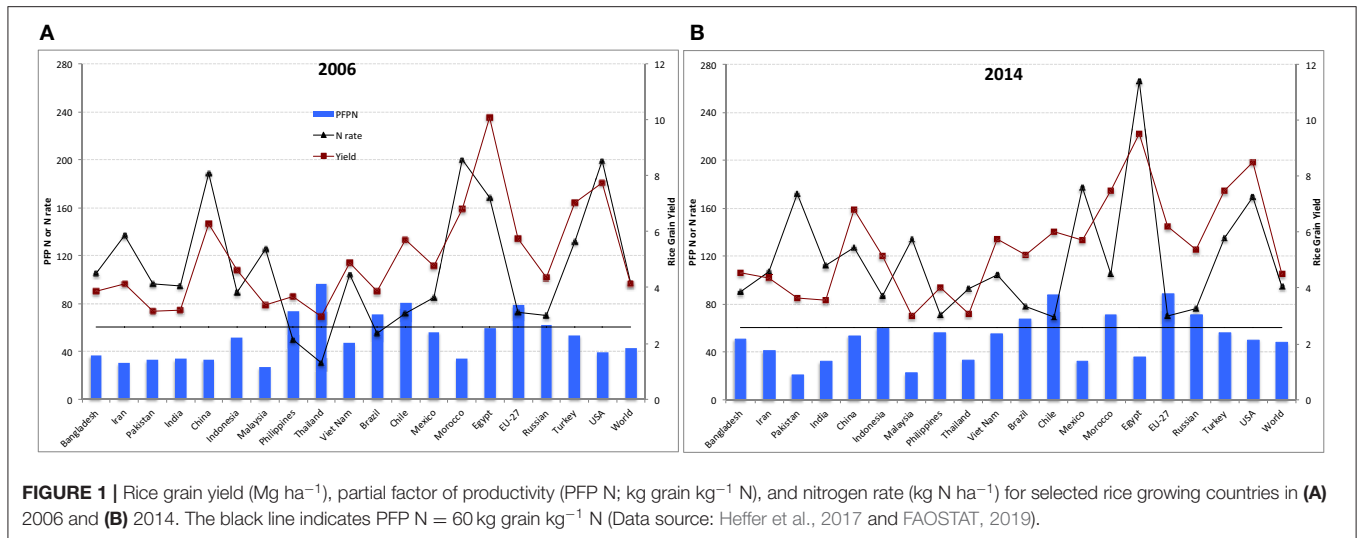
account for the increase in PFP N. The Rice Research Institute of the Guangdong Academy of Agricultural Sciences introduced the Three Controls Technology to control the amount on N fertilizer. This technology includes controls on the amount and timing of N fertilizer using site-specific nutrient management (SSNM) approach, controls on the number of tillers and controls on the use of pesticides and herbicides.

While increasing N use efficiency in rice systems is essential for sustainability, low input rice systems in Sub-Saharan Africa (SSA) are characterized by high N use efficiency, sometimes > 100 kg grain kg<sup>-1</sup> N applied. These systems are associated with mining of nutrients, resulting in land degradation (Dobermann, 2005, 2007; Edmonds et al., 2009). Africa contributes about 4.5% to global rice production (FAOSTAT, 2019). This is not enough to meet rice demand in Africa, which is increasing as dietary preferences shift from the traditional coarse grains owing to urbanization and changing family occupational structure. Rice production in SSA has increased in recent years, largely due to expansion of area than increased productivity, i.e., yield per unit area (FAOSTAT, 2019), but has been outpaced by consumption demand; much of which has been supported by imports, mostly from Asia. While global rice yields average at 4 t ha<sup>-1</sup>, yields in SSA average 2 t ha<sup>-1</sup> (GRiSP, 2013); <50% of attainable yield. This is caused by a myriad of issues, among them; low soil fertility and limited fertilizer use, use of home retained seeds and traditional varieties, labor shortage, weak markets, and lack of infrastructure and equipment for irrigation. Rice productivity in SSA can be increased via the introduction of improved cultivar and agronomic management practices.

Exploitable rice yield gaps remain in Asia and SSA (Stuart et al., 2016). There is a need for tailored solutions that are sustainable and meet the increasing global demand for food, feed, and energy while protecting the environment. Rice production also needs to be profitable for farmers; this can be partly achieved by farmers applying appropriate types and amounts of fertilizers. Fertilizers typically constitute 20% of the input costs in rice production (Pampolino et al., 2007) and achieving efficient fertilizer management is challenging in smallholder farming systems where soils and crop management can vary even within short distances. SSNM enable farmers to apply adequate and appropriate amounts of nutrients to suit soil, crop variety, and climate, hence mitigating the potential trade-offs between productivity and environmental health.

## The SSNM Approach

The SSNM approach was developed in the 1990s to calculate field-specific requirements for fertilizer N, P, and K for cereal crops, taking into consideration the indigenous nutrient supply and the target yield (Dobermann et al., 2002, 2004). SSNM was initially conceptualized for small holder rice producers in Asia, where fields tend to be small with large spatial variability in terms of nutrient status and management. SSNM is based on the principles of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model (Janssen et al., 1990) to estimate the requirement for a fertilizer nutrient from the gap between the total amount of nutrient required to achieve a specific target yield and the indigenous supply of



**FIGURE 1** | Rice grain yield ( $\text{Mg ha}^{-1}$ ), partial factor of productivity (PFP N;  $\text{kg grain kg}^{-1} \text{N}$ ), and nitrogen rate ( $\text{kg N ha}^{-1}$ ) for selected rice growing countries in **(A)** 2006 and **(B)** 2014. The black line indicates  $\text{PFP N} = 60 \text{ kg grain kg}^{-1} \text{N}$  (Data source: Heffer et al., 2017 and FAOSTAT, 2019).

the nutrient (Witt and Dobermann, 2004). The approach allows balanced application of major nutrients. Timing of fertilizer application is adjusted to meet peak nutrient demand of the crop to enhance nutrient use efficiency and foster environmental sustainability. Using SSNM principles, field-, crop-, and season-specific requirements for N, P, and K are calculated at the beginning of the season (Dobermann et al., 2002; Buresh et al., 2010).

### SSNM-Based Decision Support Tools

SSNM has evolved along a research to impact pathway, with refinement in the science and methods, expansion to new geographies, and the development of decision support tools for its dissemination. Leaf color charts, typically plastic strips containing four to six panels with colors ranging from yellowish green to dark green, were developed to monitor leaf greenness, which is related to N status and thus aid assessment and adjustment of N requirements during the season (Singh et al., 2002; Witt et al., 2005). An ICT decision support tool, the Nutrient Manager, was developed to give field-specific fertilizer recommendations for rice production, initially as Microsoft Access, but it evolved to be web-based (Buresh et al., 2014) and was eventually developed as Rice Crop Manager [RCM] (Buresh et al., 2019; Sharma et al., 2019a). RCM is a web-based and open access decision tool that provides farmers with simplified, easy to follow, and appropriate nutrient management recommendations (<https://phapps.irri.org/ph/rcm/>, <http://webapps.irri.org/in/od/rcm/>). Similar tools were developed for different regions and crops: Nutrient Expert (Pampolino et al., 2012; Xu et al., 2017a) and RiceAdvice in West Africa (Zossou et al., 2020; Arouna et al., 2021). These tools can be integrated with GIS and remote sensing for holistic and precise knowledge delivery to greater numbers of farmers. The tools provide information on yield predictions, which is useful for more accurate estimation of nutrient requirements, and allow for dynamic nutrient management with mid-season nutrient management adjustments to match crop condition and needs.

### METHODS

Data from 46 published articles with studies conducted between 2001 and 2020 were compiled in a database (**Table 1**). These studies were conducted in 11 countries: eight in Asia and three in Africa. Using Web of Science, Science Direct, and Google Scholar, we used the following search terms: SSNM, SSNM rice, SSNM maize, SSNM wheat, SSNM cereals, and SSNM vs. farmers' fertilizer practice (FFP). The studies included peer reviewed journal publications, book chapters, and technical reports that show direct comparison between SSNM and FFP in the same fields. We excluded studies when SSNM was compared with other treatments such as the no input control, blanket fertilizer recommendation, government or institute recommendation, or soil test-based recommendations. We included only studies that followed the generic SSNM approach and excluded studies where factors other than fertilizer management differed between SSNM and FFP. When multiple publications reported the data from the same experiments, we used the paper with the most complete dataset. Studies were excluded if the experimental method was vague and when there are varied factors other than fertilizer management between SSNM and FFP treatments. Hence, agronomic practices except nutrient management were the same or similar in both treatments. Of the 46 studies, 23 of them conducted N omission treatment thus enabling them to calculate and report AEN (Equation 1). In some cases, AEN values were extracted from the papers. Partial factor of productivity of N (PFP N) was calculated for all studies (Equation 2).

$$\text{AEN} = [\text{GY}_N (\text{kg ha}^{-1}) - \text{GY}_0 (\text{kg ha}^{-1})] / \text{N rate} (\text{kg N ha}^{-1}) \quad (1)$$

$$\text{PFP N} = \text{GY}_N (\text{kg ha}^{-1}) / \text{N rate} (\text{kg N ha}^{-1}) \quad (2)$$

Where  $\text{GY}_N$  is the grain yield in a treatment with N application.  $\text{GY}_0$  is the grain yield in a treatment without N application.

**TABLE 1 |** A synthesis of studies conducted in rice cropping systems on different sites in different countries in Asia and Africa under different agronomic management practices that evaluated the site-specific nutrient management (SSNM) compared to the farmer fertilizer practice (FFP) in terms of grain yield, agronomic efficiency of N (AEN), partial factor productivity of N (PFP N), and gross return above fertilizer cost (GRF).

References	Country (# of sites)	Crop. system $\beta$	Residue manag. $\alpha$	Crop estab. $\psi$	Decision tool $\xi$	N rate (kg ha <sup>-1</sup> )		P rate (kg ha <sup>-1</sup> )		K rate (kg ha <sup>-1</sup> )		Grain yield (kg ha <sup>-1</sup> )		AEN (kg grain kg <sup>-1</sup> N)		PFP (kg grain kg <sup>-1</sup> N)		GRF (USD ha <sup>-1</sup> )	
						SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP
						Abdulrachman et al. (2004)	Indonesia (1)	R-R	Retained	TPR	SPAD	106	121	20	8	57	5	4,500	4,275
AfricaRice (2016)	Ghana (1)	R-R	Removed		RA	126	151	24	23	46	44	4,900	4,300			39	28	1,076	914
Alam et al. (2005)	Bangladesh (6)	R-R	Removed	TPR	LCC	130	150	26	26	38	38	5,206	4,688	19	14	40	32	1,153	1,011
Alam et al. (2006)	Bangladesh (2)	R-U	Removed	TPR	LCC	117	149	25	30	41	46	4,550	4,000	17	10	39	27	997	827
Banayo et al. (2018)	Philippines (4)	R-R	Removed	TPR	RCM	82	97	10	11	21	19	4,538	4,228			56	44	1,053	965
Singh (2014)	India (6)		Removed	TPR	LCC	99	132					6,469	6,384	23	18	67	49		
Biradar et al. (2006)	India (1)	R-U	Removed	TPR	Others	200	120	44	13	83	25	5,520	3,686			28	31	1,130	808
Budhathoki et al. (2018)	Nepal (1)	R-U	Removed	DSR	NE							5,140	4,020						
Gines et al. (2004)	Philippines (1)	R-R	Retained	TPR	SPAD	110	107	19	15	49	23	5,200	4,700	15	12	48	45	1,169	1,068
Gupta et al. (2016)	Nepal (1)	R-U	Removed	TPR	NE							5,460	4,430						
Hu et al. (2007)	China (1)	R-R	Removed	TPR	LCC	142	177					6,100	5,900			43	33		
Islam et al. (2007)	India (2)	R-R	Removed	DSR	LCC	104	129					3,908	3,848			37	30		
Khuong et al. (2007)	Vietnam (3)	R-R	Removed	DSR	Others	96	106	19	21		39	5,620	5,525	15	13	59	52		
Khurana et al. (2007)	India (6)	R-U	Removed	TPR	SPAD	136	148	11	3	30	0	6,000	5,117	17	9	44	35	1,376	1,180
Khurana et al. (2009)	India (1)	R-U	Removed	TPR	Others	137	148					6,000	5,050	16	10	44	34		
Mandal et al. (2015)	India (1)	R-U	Removed	TPR	NE	111	85	14	23	41	39	5,784	4,627			52	54	1,326	1,041
Marahatta (2017)	Nepal (1)	R-U	Removed	TPR	Others	96	53	19	11	60	7	6,350	4,620			66	88	1,459	1,099
					LCC	100	53	19	11	60	7	6,660	4,620			67	88	1,533	1,099
Nagarajan et al. (2004)	India (2)	R-R	Retained	TPR	SPAD	129	98	22	22	75	35	6,021	5,350	15	14	47	57	1,340	1,218
Pampolino et al. (2007)	India (2)	R-R	Removed	TPR	LCC	125	115	14	20	66	36	6,425	6,000			52	53	1,463	1,373
	Philippines (2)	R-R	Removed	TPR	LCC	113	125	12	17	48	31	5,200	4,850			46	42	1,178	1,087
	Vietnam (3)	R-R	Removed	DSR	LCC	92	106	20	20	36	41	4,917	4,583			54	44	1,116	1,021
Pampolino (2016)	India (1)	R-U	Removed	TPR	NE	111	85	15	17	41	39	5,780	4,630			52	54	1,325	1,051
	China	R-U	Removed	TPR	NE	156	170	31	26	72	71	8,000	7,800	15	12	51	46	1,806	1,756

(Continued)

TABLE 1 | Continued

References	Country (# of sites)	Crop. system $\beta$	Residue manag. $\alpha$	Crop estab. $\psi$	Decision tool $\xi$	N rate		P rate		K rate		Grain yield		AEN		PFP		GRF	
						(kg ha <sup>-1</sup> )		(kg ha <sup>-1</sup> )		(kg ha <sup>-1</sup> )		(kg ha <sup>-1</sup> )		(kg grain kg <sup>-1</sup> N)		(kg grain kg <sup>-1</sup> N)		(USD ha <sup>-1</sup> )	
						SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP	SSNM	FFP
Peng et al. (2006)	China (4)	R-R	Removed	TPR	SPAD	87	205	40	40	100	100	7,544	7,163	13	4	98	35	1,704	1,532
	Philippines (1)	R-R	Removed	TPR	SPAD	133	90	30	30	40	40	6,650	6,150	20	23	51	68	1,505	1,407
Tan et al. (2004)	Vietnam (1)	R-R	Retained	DSR	SPAD	98	112	22	20	62	20	4,663	4,390	20	15	48	40	1,029	983
Qureshi et al. (2018)	India (1)	R-U	Removed	TPR	NE	118	130	12	17	43	17	6,531	6,064	25	19	55	47	1,511	1,394
Rajendran et al. (2010)	India (2)	R-R	Removed	TPR	LCC	121		15		50		6,363	5,825						
Saito et al. (2015)	Senegal (1)		Removed	DSR	RCM	133	153	17	18	26	0	7,467	5,967			57	39	1,738	1,365
Satawathananont et al. (2004)	Thailand (1)	R-R	Retained	DSR	SPAD	112	112	18	23	43	5	4,795	4,725	9	8	43	43	1,071	1,070
Segda et al. (2005)	Burkina Faso (1)	R-R	Removed	TPR	Others	116	79	21	16	20	15	6,440	5,203			56	66	1,490	1,215
Sharma et al. (2019a)	India (1)	R-R	Removed	TPR	NE	127	122	14	21	38	46	4,833	4,300			38	36	1,081	935
Sharma et al. (2019b)	India (4)	R-R	Removed	TPR	RCM	102	85	13	22	28	44	5,094	4,561			50	55	1,170	1,023
Singh et al. (2015)	India (1)	R-U	Removed	TPR	Others	180		26		75		9,110	6,800						
Son et al. (2004)	Vietnam (1)	R-U	Retained	TPR	SPAD	94	104	16	20	53	62	6,175	6,013	18	14	67	58	1,425	1,366
Van Hach and Tan (2007)	Vietnam (3)	R-R	Removed	DSR	LCC	99	113	17	21	40	40	5,807	5,447			59	49	1,335	1,231
Varinderpal et al. (2010)	Bangladesh (1)	R-R	Removed	TPR	SPAD							5,100	5,000	26	17				
	India (13)	R-R	Removed	TPR	LCC	68	92					5,656	5,540			99	76		
Wang et al. (2001)	China (1)	R-R	Removed	TPR	SPAD	133	171	21	22	80	75	6,350	5,900	11	6	48	34	1,419	1,283
Wang et al. (2004)	China (1)	R-R	Removed	TPR	SPAD	126	171	14	19	52	57	6,475	6,192	12	7	52	36	1,483	1,371
Wang et al. (2007)	China (2)	R-R	Removed	TPR	SPAD	136	236	14	19	52	58	8,240	7,770	16	9	61	35	1,743	1,599
Wang et al. (2020)	China (1)			DSR	NE	169	185	29	33	75	73	9,400	9,200	20	17	56	50	1,208	1,163
Xu et al. (2010)	China (1)	R-R	Retained	TPR	SPAD	102	150	39		62		6,538	6,550			64	44		
Xu et al. (2017a)	China (3)	R-R	Removed	TPR	NE	156	191	30	34	76	88	8,342	7,858	17	13	54	42	1,890	1,733
Yang et al. (2017)	China (7)	R-R	Removed	TPR	NE	156	169	30	26	66	70	8,429	7,957	17	14	54	48	1,917	1,795

Country (# of sites) is country where study was conducted and in parenthesis is the number of sites within the country.

Crop. system  $\beta$  is cropping system where R-R is rice-rice; R-U is rice-upland crop.

Residue manag.  $\alpha$  is residue management.

Crop estab.  $\psi$  is crop establishment method; TPR is transplanted and DSR is direct seeded rice.

Decision tool  $\xi$ : SPAD is SPAD chlorophyll meter; LCC is leaf color chart; NE is nutrient expert; RA is RiceAdvice; RCM is Rice Crop Manager.

Averages of yields and AEN of both SSNM and FFP were obtained from each study, while in some instances, manual estimation from the figures was performed when these data were only presented in figures. Individual studies have variable number of replicates with 323 as the highest number. Also, nutrient rates among the fields varied and were reported as a range because there is a high spatial variability even for neighboring fields. Thus, the average between the minimum and maximum values reported was determined across the replicates and was used as nutrient rate for the reported grain yield. The most common sources of fertilizers used in the studies were urea for nitrogen, DAP for P, and muriate of potash (KCl) for potassium.

The cost benefits were reported as gross return above fertilizer cost (GRF) in this paper, which was derived from the other two economic performance metrics: total fertilizer cost (TFC; Equation 3) and gross return (Equation 4). GRF was calculated as in Equation 5. Fertilizer prices of the most common sources: urea (46-0-0) for N, DAP (18-46-0) for N and P, and KCl (0-0-60) for K (urea, DAP, and KCl), were estimated from the 10-year average across countries listed in the database (Indexmundi, 2020; <https://www.indexmundi.com>). The prices were calculated as per unit of nutrient leading to US\$0.642 kg<sup>-1</sup> N, US\$2.151 kg<sup>-1</sup> P, and US\$0.633 kg<sup>-1</sup> K. Farm gate price of paddy rice was used at US\$0.25 kg<sup>-1</sup> paddy rice based on the trend of the market price for the past 25 years (Indexmundi, 2020; <https://www.indexmundi.com>).

$$\text{TFC (US\$ ha}^{-1}\text{)} = (\text{pN} \times \text{N}_{\text{rate}}) + (\text{pP} \times \text{P}_{\text{rate}}) + (\text{pK} \times \text{K}_{\text{rate}}) \quad (3)$$

$$\text{Gross return (US\$ ha}^{-1}\text{)} = \text{FGP} \times \text{GY} \quad (4)$$

$$\text{GRF (US\$ ha}^{-1}\text{)} = \text{Gross return} - \text{TFC} \quad (5)$$

Where pN, pP, pK = prices of N, P and K fertilizers, respectively (US \$ kg<sup>-1</sup>).

N<sub>rate</sub>, P<sub>rate</sub>, K<sub>rate</sub> = amount of N, P, and K applied (kg ha<sup>-1</sup>).

FGP = farm gate price of paddy rice, maize, or wheat (US\$ kg<sup>-1</sup>).

GY = grain yield of paddy rice, maize, and wheat (kg ha<sup>-1</sup>).

## Performance of SSNM

We conducted a mini-review using 46 studies (43 from Asia and three from SSA). This shows the paucity of research in SSA, despite the low rice productivity against an increasing rice demand in the region. Our analysis shows that on average, the implementation of SSNM recommendations resulted in 644 kg ha<sup>-1</sup> (11.4%) more rice yield compared to the farmer fertilizer practice (FFP; **Table 1**). This was associated with 38.2, 18.2, and 8.6% greater agronomic efficiency of N, PFP N, and gross return above fertilizer cost (GRF; a measure of economic performance) with SSNM compared to FFP, respectively. These benefits accrued while using 14% less N fertilizer than FFP (**Table 1**), similar to observations by Peng et al. (2010). The lower N fertilizer also resulted in an increased GRF by US\$178 ha<sup>-1</sup> and a higher agronomic N use efficiency (AEN) under SSNM (17 kg grain kg<sup>-1</sup> N) than FFP (12 kg grain kg<sup>-1</sup> N applied) and PFP N (58 vs. 47 kg grain kg<sup>-1</sup> N). The FFP is often based on blanket recommendations with unbalanced nutrient application in many

cases (Wang et al., 2001; Dobermann et al., 2002; Peng et al., 2010).

Increased N use efficiency in SSNM was attributed to the distribution of N fertilizer applications (i.e., timing, amount, and frequency), resulting in an optimized balance between N supply and crucial stages of crop growth and demand for N. On average, there were 3.5 N-fertilizer splits under SSNM compared to 3.0 under FFP. In addition to reduced N fertilizer, the SSNM approach ensures balanced N, P, and K application contributing to increased N use efficiency. In our review, the largest increases in N use efficiency with SSNM were observed in China, where farmers generally use excessive amounts of N fertilizer (Wang et al., 2001; Peng et al., 2010). Peng et al. (2010) reviewed the performance of SSNM across 107 sites in China conducted over 10 seasons and showed on average, higher N input in FFP (195 kg N ha<sup>-1</sup>) compared to SSNM (133 kg N ha<sup>-1</sup>). While that study showed a 5% yield advantage with SSNM, the greater benefits were observed with AEN, which was 61% higher compared to FFP. This suggests significant reduced N losses.

Although most of the reviewed studies were in irrigated lowland ecosystems, where the SSNM approach was developed, Biradar et al. (2006) and Banayo et al. (2018) in India and in the Philippines, respectively, conducted studies under rain-fed ecosystems and reported higher rice yield and GRF under SSNM compared to FFP. However, the higher yield for SSNM in India was achieved with about 1.7 times more N fertilizer than in FFP, resulting in a lower PFP N under SSNM. It is likely that the algorithms of SSNM evaluated a greater N requirement in rain-fed systems but that could be an overestimation since SSNM has not been optimized with limited trials under rain-fed systems. Overestimation could lead to lower PFPN, thus further evaluation and calibration of SSNM under rain-fed environments are needed.

Rice yield, N use efficiencies and GRF responses to SSNM recommendations varied depending on crop establishment methods. Greater benefits from SSNM compared to FFP were observed for transplanted than direct-seeded rice (DSR; **Table 1**). Faced with labor and water scarcity in transplanted systems (Pampolino et al., 2007), farmers are increasingly adopting DSR (Kumar et al., 2018). However, weeds are a major constraint in DSR systems, leading to reduced crop productivity. A key strategy to enhance rice yield under DSR is to apply N late in the season (Liu et al., 2019), this is in line with SSNM which emphasizes the need to time N supply with demand. There are opportunities for improving SSNM recommendations for DSR, encompassing local conditions and weed management.

Traditional tools based on leaf greenness to assess N status (leaf color charts and SPAD or chlorophyll meter) were used in 21 of the studies and increased rice yield, PFP N and GRF by 6.8, 18.9, and 9.1%, respectively, compared to FFP (**Table 1**). On the other hand, the use of SSNM-based digital decision-support tools (RCM, Nutrient Expert, RiceAdvice) increased rice yield by 11.7%, PFP N by 11.5%, and GRF by 11.8%. However, RiceAdvice was only used in one study (AfricaRice, 2016). Digital tools provide pre-season recommendations, and allow for in-season N fertilizer adjustments to improve the performance of the recommendations given by the tools. However, extensive

adoption of SSNM-based digital tools by farmers in the field has been limited by factors like poor access to the tools, non-availability of internet facilities, low penetration of digital devices in rural areas, non-availability of recommended fertilizers, limited credit for buying the fertilizers, labor shortage lack of concentrated efforts by the local extension agents (Florey et al., 2020). Integrating digital tools with geospatial approaches facilitates improved yield targets and in-season N adjustment based on crop performance and enhances scaling of SSNM recommendations (Xu et al., 2017b).

## DISCUSSION

Our mini-review shows SSNM as an effective N management strategy for improving rice productivity and profit for farmers while increasing N use efficiency, thus attaining environmental benefits. On average, optimized nutrient management reduced N fertilizer inputs, improved yields, and hence, increased N use efficiency. While N use efficiency has been used to indicate the balance between N used for grain production and losses to the environment (Dobermann, 2007; Omara et al., 2019), only a few studies have quantified N losses under SSNM. For example, a recent study using Nutrient Expert showed both agronomic and environmental benefits of SSNM in a rice–maize cropping systems in China (Wang et al., 2020). In that study, N losses and GHG emissions with SSNM were 10.1 and 6.6% lower than FFP for rice and 46.9 and 37.2% for maize, respectively. The reduced losses arose from increased N use efficiency. Nutrient Expert was also used for winter wheat in North China where N fertilizer rates were 41.4% lower with SSNM than FFP, leading to a 70% increase in agronomic N use efficiency and 55% lower emissions of N<sub>2</sub>O (Zhang et al., 2018).

Similarly, using Nutrient Expert in a wheat cropping system in India, GHG emissions were 16–42% lower under SSNM than FFP, both under conventional and no-till, but with greater benefits under no-till (Sapkota et al., 2014). Sapkota et al. (2021) observed a 2.5% reduction in global warming potential associated with reduced GHG emissions, increased rice yields and profit in India when Nutrient Expert was compared to FFP. Earlier studies in the Philippines and Vietnam (Pampolino et al., 2007) and in China (Wang et al., 2007) also showed increased N use efficiency with reduced N losses through leaching, runoff, and N<sub>2</sub>O emissions with SSNM compared to FFP. SSNM, hence, provides a climate mitigation nutrient management option compared with the FFP. Considering the wide range of conditions where rice is grown, there is need to evaluate the benefits of SSNM in more locations and using different digital tools. However, adoption of SSNM recommendations has been low, highlighting the need to strengthen extension systems through public and private partnerships.

Currently, the SSNM-based digital tools, including RCM, provide pre-season nutrient management recommendations and focus on balanced application of N, P, and K with little emphasis on micronutrients. On the other hand, farmers generally lack awareness of the importance of micronutrients and there are less obvious and/or immediate yield gains and profit associated with

micronutrient fertilization. This has resulted in mining of these micronutrients from rice soils, while malnutrition, particularly due to zinc and iron deficiency, is common for communities relying on rice-based diets (Palanog et al., 2019). While much of the research on improving micronutrient nutrition in rice have been through breeding (Dixit et al., 2019), there is also need to optimize micronutrient management, along with major nutrients, for the production of healthier rice through agronomic bio-fortification as soil or foliar application (Hakoomat et al., 2014). Given that more iron and zinc is needed during the early growth stages of rice, application in the soil is more practical than foliar application, which requires the plant leaves to have been developed significantly in order to effectively take up the foliar applied nutrients. However, zinc has been shown to convert to unavailable forms immediately after the application of zinc sulfate in flooded soils (Bunquin et al., 2017). Thus, soil application of zinc is not highly effective in flooded rice fields. Although foliar application of zinc at later growth stages of rice does not result in yield gain, it has been shown to increase grain zinc content and is therefore important for the production of healthier high-zinc rice (Hakoomat et al., 2014; Rubianes et al., 2018).

While micronutrient fertilization improves the nutrition value of rice grain, farmers are often not compensated for the extra input costs. They are unwilling to invest in micronutrient management in the absence of other incentives. Policy shifts are needed to reward farmers for the production of more nutritious and healthier rice; some of them necessarily require active public–private partnerships. For example, the Sustainable Rice Platform, which is promoting a premium price for sustainably produced rice (SRP, 2019). Such efforts can foster environmental sustainability, ensuring that rice systems in the Global South deliver essential ecosystem services while also improving farmers' livelihoods. The changing climate and other driving forces like shortage of labor and water dictate shifts from continuous intensive rice systems to changes in agronomic management practices, such as direct seeded rice, non-puddled rice, and water saving technologies. Increasing rice productivity while minimizing adverse environmental consequences require the adoption of integrated nutrient and crop management practices that increase system-level efficiency.

## CONCLUSION

Our mini-review clearly shows that SSNM in rice cropping systems increases rice yield, profit, and N use efficiency while reducing N losses and GHG emissions when compared with the farmer practice. AEN and PFP were 38.2 and 18.2% greater with SSNM than the farmer practice. This was achieved using 14% lower N fertilizer. The superior performance of SSNM compared to the farmer practice is mainly due to better distribution with more splits of N fertilizer during the growing season coupled with balanced fertilization. However, SSNM has mainly focused on the major nutrients, ignoring micronutrients, and thus, impacting human nutrition for those whose diets are rice-based, while potentially mining the soils of the micronutrients. SSNM-based

digital decision support tools enable dissemination of SSNM recommendations at scale, but this requires a pluralistic approach that fosters collaboration among multiple organizations and service providers with support from governments. Additionally, linking the digital tools with GIS and remote sensing tools allows fine-tuning of SSNM recommendations, addressing the huge spatial variability in smallholder farming systems. SSNM research and evaluation has focused on favorable environments in Asia, despite the increasing demand and production in Africa. More research is needed on SSNM under diverse management practices, such as direct seeding, and in marginal environments along with quantification of nutrient losses, along with inter-disciplinary approaches to enhance farmer uptake of SSNM.

## AUTHOR CONTRIBUTIONS

PC, SS, and JH conceived the project. MB extracted data from publications. PC and MB conducted analyses. PC wrote

the manuscript draft. All authors contributed to the literature search, interpretation of the results, and writing of the final paper.

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