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Revisiting fertiliser strategies: Customised fertilisers for enhanced nutrient uptake, yield and profitability

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Abstract

Fertilisers are essential for increasing agricultural output and ensuring food security. In India, fertiliser consumption has increased substantially to 32.93 million tonnes by 2025 and the imbalanced and excessive use of fertilisers has led to declining soil fertility and reduced fertiliser use efficiency (FUE). In this context, customised fertilisers (CFs) have emerged as an effective strategy to address these challenges by providing balanced nutrition tailored to specific soil and crop requirements. These multi-nutrient fertilisers improve nutrient availability, correct deficiencies and enhance crop uptake of nutrients. Customised fertilisers also support precision nutrient management by aligning fertiliser application with soil test values and crop demand, thereby minimising nutrient losses and preventing soil degradation. Additionally, CF reduce labour, time and cost associated with fertiliser application. This review highlights how the gradual and need-based nutrient release from CF improves soil nutrient availability, crop nutrient uptake, FUE and crop productivity. Studies have shown that the use of CF increased nutrient availability and nutrient uptake by up to 45 %, while crop yield increased by 9–22 % in rice, 16–33 % in wheat and 15–20 % in chickpea compared to conventional fertilisers. These values represent ranges reported across individual studies. Overall, CF offer a sustainable approach for improving FUE, crop productivity and soil health.

Keywords: customised fertiliser; fertiliser use efficiency; soil health; sustainable agriculture

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1. Introduction

Fertilisers are vital inputs for enhancing agricultural production and are integral components of integrated nutrient management of crops. Fertiliser usage in India increased with the introduction of fertiliser responsive high-yielding cultivars in the mid-1960s, ushering in the green revolution and resulting in self-sufficiency in food grain production. However, the continuous decline in soil fertility has resulted in a gradual rise in the application of nitrogen (N), phosphorus (P) and potassium (K) fertilisers to maintain crop productivity. For instance, during 1971–72, India produced 105.2 million tonnes of food grains with fertiliser consumption of 1.80 million tonnes N, 0.56 million tonnes phosphorus pentoxide (P_2O_5) and 0.30 million tonnes potassium oxide (K_2O). Over more than five decades by 2024–25, food grain production had tripled, whereas fertiliser consumption increased disproportionately by 12.3 times for N, 15 times for P_2O_5 and 7.9 times for K_2O. By 2024–25, India had become the world's second-largest fertiliser consumer (1). Evidence suggests that farmers often apply N and P in excess of recommended levels while neglecting adequate application of K, as well as secondary and micronutrients (2). Such imbalance in nutrient management reduces nutrient use efficiency (N: 30–40 %, P: 15–20 %, K: 60–80 %, S: 8–10 % and micronutrients like iron (Fe), manganese (Mn), copper (Cu), zinc (Zn) and boron (B): 2–5 %) and crop productivity, while also increasing environmental risks due to nutrient losses through emissions and leaching (3). These alarming declining trends in soil health and crop productivity have compelled researchers to evolve an alternate strategy for achieving higher productivity and optimum soil health. This necessitates better management of applied fertilisers and improvement in fertiliser use efficiency (FUE) through the use of customised fertilisers.

2. Methodology

Study design and PRISMA compliance

This systematic review was conducted in accordance with the preferred reporting Items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines to ensure transparency, reproducibility and methodological rigour (Fig. 1). The review methodology was systematically designed to assess the current status and research progress of customised fertilisers (CF) in agriculture.

Search strategy and information sources

A comprehensive literature search was carried out using four major electronic databases: Scopus, Web of Science, CABI Direct and Google Scholar. The search included peer-reviewed articles published up to the present year. The keywords employed during the search process included "customised fertilisers", "site-specific nutrient management", "speciality fertilisers", "tailored fertilisers", "smart fertilisers", "new-generation fertilisers" and "fertiliser use efficiency". To improve reproducibility, the database-specific search strings were structured as follows: Scopus: ("customised fertilisers" or "site-specific nutrient management" or "speciality fertilisers" or "tailored fertilisers"); Web of Science: ("customised fertilisers" or "smart fertilisers" or "new-generation fertilisers" or "fertiliser use efficiency"); CABI Direct: ("customised fertilisers" or "speciality fertilisers" or "tailored fertilisers" or "smart fertilisers" or "new-generation fertilisers"); Google Scholar: ("customised fertilisers" or "site-specific nutrient management" or "speciality fertilisers" or "tailored fertilisers" or "smart fertilisers" or "new-generation fertilisers" or "novel fertilisers"). A comprehensive literature search was conducted using four electronic databases, namely Scopus, Web of Science, CABI Direct and Google Scholar, during the period from 10 April 2025 to 25 February 2026. The search covered peer-reviewed studies published up to 25 February 2026.

Eligibility criteria (inclusion/exclusion)

Studies were included in the review if they met the following criteria: (i) original research studies focusing on the application of customised fertilisers; (ii) comparative studies evaluating CF against conventional fertilisers; and (iii) articles published in English language.

Studies were excluded if they (i) focused exclusively on conventional fertilisers without involving customised fertilisers; (ii) consisted of editorials, conference abstracts lacking complete experimental data or non-peer-reviewed publications.

Selection process and data synthesis

As presented in the PRISMA flow diagram, the initial database search identified 198 records (Scopus = 70, Web of Science = 24, CABI Direct = 55 and Google scholar = 49). After removal of 75 duplicate records, 123 records remained for title and abstract screening. Of these, 63 records were excluded because they were irrelevant to CF or focused on non-agricultural applications. The remaining 60 full-text reports were assessed for eligibility and all 60 eligible studies were included in the final qualitative and quantitative synthesis.

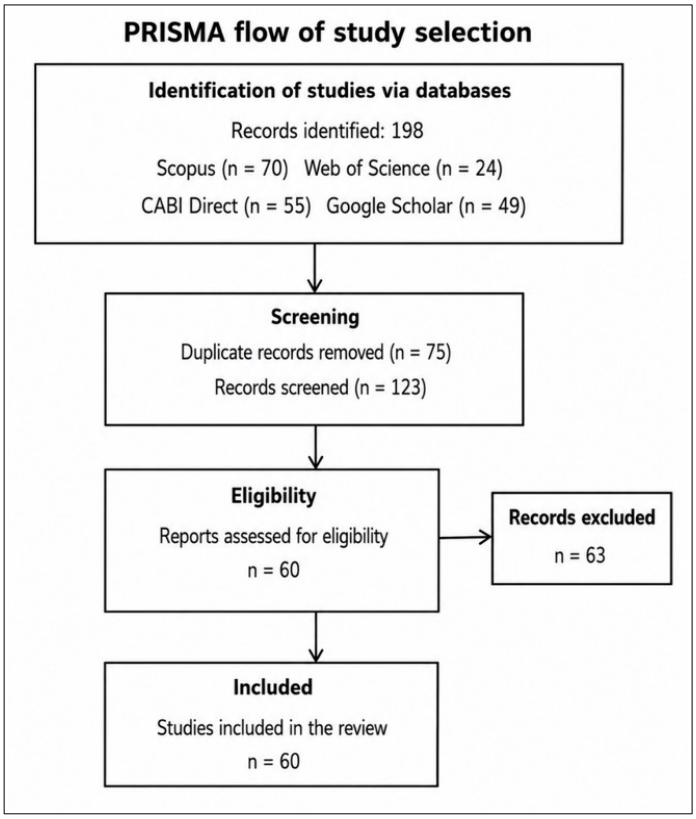


Fig. 1. PRISMA methodology on customised fertilisers.

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Customised fertilisers

Customised fertilisers are multi-nutrient fertilisers formulated based on soil fertility status, crop nutrient requirements and agro-climatic conditions (4). Unlike conventional fertilisers that supply one or two nutrients, CF provide a balanced combination of macro and micronutrients in a single formulation (5).

History

The development of CFs in India involved participation from major fertiliser companies such as Tata Chemicals Limited (TCL), Nagarjuna Fertilisers, Coromandel International Limited (CIL) and Deepak Fertilisers. Tata Paras Farmoola was the first customised fertiliser in India, scientifically developed by Tata Chemicals Limited. It is a granular chemiscal fertiliser customised as per region and crop. Paras Farmoola contains all primary, secondary and micronutrients critical for that region or crop in ideal proportion. Field experiments on sugarcane demonstrated that the application of paras customised fertiliser containing N : P : K : S : Zn : B in the ratio of 7 : 20 : 18 : 6 : 0.5 : 0.2 resulted in higher yield compared to the conventional fertiliser practices (6). When the Indian government launched the Nutrient Based Subsidy (NBS) program in April 2010, other companies including Coromandel International Limited, Deepak Fertilisers and Petrochemicals Corporation Limited (DFPC) and Nagarjuna Fertilisers and Chemicals Limited (NFCL) also initiated efforts to develop and market customised fertiliser products.

Customised fertilisers comparison with other advanced technologies

Customised fertilisers differ from other advanced fertiliser technologies mainly in their approach to nutrient management are presented in Table 1.

Customised fertilisers and related nutrient-management approaches

Customised fertilisers are physical fertiliser formulations in which the nutrient composition is tailored to the crop, soil fertility status and agro-climatic conditions. Site-specific nutrient management (SSNM) is a decision-support approach that determines the right nutrient source, rate, time and place for a specific field or management zone. Smart fertilisers (including controlled release, nano-enabled and biobased nutrient carriers) are promising innovations that could address these problems. Smart fertilisers indeed fit very well with sustainable and resilient agriculture, as they allow for greater efficiency and better soi-plant interactions, while exerting lower environmental pressure. Specialty fertilisers are classified as slow and controlled release fertilisers, stabilised fertilisers, agrochemicals compatible with fertilisers, fortified fertilisers, organically chelated micronutrients and highly water-soluble fertilisers. These are fully water-soluble solid fertiliser products, having high content of primary nutrients with low salt index. Secondary or micronutrients may or may not be the constituents of these products. Thus, a customised fertiliser may be used as one component within SSNM or precision nutrient management, but the terms should not be used interchangeably.

Need for customised fertilisers

Customised fertilisers are considered useful for implementing site-specific nutrient management because they can supply multiple nutrients in proportions suited to a particular crop and soil situation. Site-specific nutrient management is primarily based on the “4R” principle-right source, right rate, right time and right place. Uniform application of fertilisers at fixed rates has reduced FUE and contributed to the emergence of widespread nutrient deficiencies. Moreover, prolonged intensive cultivation has hastened the depletion of soil nutrients, creating a considerable nutrient imbalance. Currently, deficiencies of both macro and micronutrients are prevalent, highlighting the importance of SSNM as a viable strategy to overcome these challenges (11). With the use of customised fertilisers, separate purchase and mixing of different fertilisers can be avoided, thereby easing farm labour and also saving time and costs associated with fertiliser application (12). From an environmental safety perspective, reducing excessive fertiliser application through the use of CFs can substantially decrease greenhouse gas emissions, in some cases by up to 50 % (13, 14). Hence, under fertiliser management, CFs assume considerable significance in improving FUE. Pre-formulated, crop-specific CFs have a vital role in alleviating nutrient stress in plants, thereby enhancing nutrient availability and yield of crops.

Table 1. Customised fertilisers comparison with other advanced technologies

Technology	Main approach	Major advantage	Major limitation	References
Customised fertilisers	Crop- and region-specific combination of nutrients	Corrects multiple nutrient deficiencies through a single formulation	Requires reliable soil data and region-specific formulation	(5)
Nano-fertilisers	Nano-scale nutrient delivery	Potential for improved nutrient-use efficiency and controlled delivery	Field validation, cost and long-term environmental safety remain concerns	(7)
Bio-fertilisers	Beneficial microorganisms improve nutrient availability	Eco-friendly nutrient mobilisation and biological N fixation	Performance varies with soil, climate and microbial strain	(8)
Precision agriculture	Sensors, GIS/GPS and variable-rate nutrient application	Addresses spatial variability within fields	Requires technology, data, expertise and initial investment	(9)
Controlled-release fertilisers	Coatings regulate nutrient release	Synchronises nutrient release with crop demand and reduces nutrient losses	Higher material/manufacturing cost	(10)

GIS: global information system; GPS: global positioning system.

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Procedure for development of customised fertiliser (15)

Selection of target area and crop: Customised fertilisers are specific to region and crop, so the first step is to define the study area and crops. Agro-ecological regions are ideal units for this purpose. The target area should be sufficiently characterised for soil fertility, climate, cropping pattern and prevailing management practices before formulation. Instead of developing many fertiliser grades for narrowly defined units, an average-based approach may be used where it adequately represents the dominant soil and crop conditions. Average or weighted-average soil fertility values are commonly used to develop region-specific customised fertilisers. However, average values may not represent the actual nutrient status of every field because soil fertility varies with soil type, cropping history and fertiliser management. As a result, the same formulation may supply excess nutrients to some fields and insufficient nutrients to others. Therefore, regional formulations should be supported by representative soil sampling and field validation.

Building database: A detailed database on soil fertility and crop requirements is essential. Using georeferenced maps, the research region is divided into grids (about 1 × 1 km). Soil samples are collected from each grid point using global positioning system (GPS). Information on farmer practices is also recorded. Crop samples are collected to measure yield and nutrient uptake. These data are analysed using geographic information system (GIS) tools to identify spatial patterns in nutrient availability and crop demand. Challenges in database development and GIS mapping: Their accuracy largely depends on the number and distribution of soil samples, sampling methods and laboratory analysis. In addition, soil fertility changes over time due to continuous cropping and nutrient management. Therefore, soil databases and GIS-based fertility maps need to be regularly updated to provide reliable fertiliser recommendations.

Concept of fertility management zones: Soil data are used to create maps showing nutrient status (N, P and K). By combining these maps, different fertility zones are identified. These zones help in deciding nutrient requirements. Analysis also helps identify important secondary and micronutrients.

Establishment of nutrient requirement: Actual crop yield (obtained from crop cutting experiment and farmers surveys) and potential yield (obtained from dynamic crop growth models like INFOCROP) are compared to identify yield gaps. Based on this, a realistic target yield is fixed. Nutrient uptake data are used to estimate nutrient requirements for achieving the target yield. Crop varieties are also considered, as nutrient needs vary among them.

Fixing fertiliser grade: Soil fertility status and crop nutrient requirements were integrated using soil test crop response (STCR) -based fertiliser adjustment equations, empirical models such as quantitative evaluation of the fertility of tropical soils (QUEFTS) and crop-specific nutrient response studies to develop suitable nutrient combinations and application rates. However, yield-specific recommendations for secondary and micronutrients remained a major challenge, as existing models were inadequate for these nutrients. Hence, critical limits and the law of restitution were considered for their estimation. Considering nutrient interactions and repeated nutrient supply through customised fertilisers, micronutrient levels were adjusted below the conventional restitution-based recommendations.

Grade preparation and validation: Different fertiliser combinations are prepared and tested in field trials. Trials are conducted at multiple locations under on farm conditions. Results are evaluated based on crop yield, quality and economic returns. Yield increases of 8–26 % were observed compared to traditional practices. The best-performing grades are selected based on efficiency and profitability.

Commercialisation of customised fertiliser: After approval, fertilisers are produced and marketed. Manufacturing involves grinding raw materials, mixing them uniformly and forming granules using steam granulation. Large-scale plants are established for production.

Effects of customised fertilisers on soil fertility, nutrient use efficiency, crop productivity and economics

Influence on soil nutrient availability and uptake in crops

Customised fertilisers provide a balanced and adequate supply of both macro and micronutrients, thereby enhancing nutrient availability in the soil. Customised fertilisers provide a balanced and adequate supply of both macro and micronutrients, thereby enhancing nutrient availability in the soil. Application of CFs has been reported to significantly improve soil nutrient availability compared to conventional fertiliser practices. This improvement is attributed to the balanced nutrient composition, which supports the buildup and sustained availability of nutrients (16, 17). The inclusion of micronutrients in CFs plays a critical role in overcoming hidden hunger and enhancing crop productivity (18).

Soil test-based customised nutrient management improves nutrient availability by supplying nutrients in site-specific proportions, which not only enhances crop yield but also prevents soil degradation caused by excessive or imbalanced fertiliser application. For instance, a nutrient mixture specifically formulated for rice grown in acid saline soils of Kerala, containing N (1.60 %), K (12.5 %), Ca (1.88 %), Mg (5.05 %), Mn (0.16 %), Cu (0.70 %), Zn (1.20 %) and B (2.31 %), demonstrated the importance of targeted nutrient application in improving soil fertility (19). Similarly, in Onattukara soils under rice cultivation, the combined use of organic and mineral fertiliser mixtures was recommended to reduce nutrient losses through leaching. Such integrated approaches enhance nutrient retention by minimising losses through runoff and leaching, thereby improving overall nutrient availability in the soil (20).

Improved nutrient availability and balanced nutrition ultimately enhance nutrient uptake by crops. Nutrient uptake is primarily a function of both biomass production and nutrient concentration in plant tissues. In crops, the application of CFs has been shown to enhance

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nutrient uptake in both grain and stover compared to conventional fertilisers, mainly due to the balanced supply of macro- and micronutrients and their improved availability in the soil (21).

Effects of CFs on nutrient availability and uptake have been reported across various studies and are presented in Table 2 and 3.

Enhancement of fertiliser use efficiency

Fertiliser use efficiency evaluates how effectively crops convert applied nutrients into economic yield. It can be expressed in several ways.

Agronomically, FUE is expressed as units of yield improvement per unit of applied nutrient. It can be computed as follows: AE (kg kg^{-1}) = Yf–Y0 /Fa, where Yf is the yield from fertilised plot (kg), Y0 is the yield from the control plot and Fa is the amount of fertiliser applied (kg). The use of CFs improves agronomic efficiency (AE) by supplying plant nutrients in adequate amounts at the right time, which accelerates cell division and elongation. As a result, plants grow more rapidly and develop a vigorous root system that enables efficient uptake of nutrients from deeper soil layers. The improved nutrient contribution further enhances growth and yield attributes, ultimately leading to higher overall crop yield (28).

Physiological efficiency (PE), it is expressed as units of increased yield per unit of nutrients absorbed by the crop. It can be computed as: PE (kg kg^{-1}) = (Yf-Y0 / Nf-N0) × 100, where, Yf is the fertilised plots yield (kg), Y0 is the yield from the control plot and Nf is the nutrient uptake in above ground biomass from fertilised plot (kg), N0 is the nutrient uptake in above ground biomass from control plot (kg). Customised fertilisers ensure balanced nutrition by supplying nutrients in a slow and consistent manner. This helps maintain leaf greenness for a longer duration and improves the rate of photosynthesis. As a result, dry matter production increases and the movement of photosynthates towards sink organs becomes more efficient (29).

Table 2. Influence of customised fertilisers on soil nutrient availability

Crop	Location	CF composition	Increase in soil nutrient availability								
			N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Zn (%)	Cu (%)	B (%)	References
Rice	Uttar Pradesh	100 % CF – N : P_2O_5 : K_2O : Zn : B (10 : 26 : 17 : 1 : 0.3 %)	+10	+6.9	-	-	-	+1.5	-	+20	(22)
Maize	Tamil Nadu	CF along with micronutrients	+45.47	+40.98	+21.14	-	-	+59.47	+36.90	-	(21)
Soybean	Chhattisgarh	150 % CF - N : P : K (56.25 : 63.75 : 41.25 Kg ha^{-1})	+21.33	+27	-	-	-	-	-	-	(16)
Oriental pickling melon	Kerala	N : P : K : Ca : Mg : S : Fe : Zn : B : Cu : Mn	+26.19	-	+7.64	+7.28	+4.12	-	+9.49	-	(23)

Yield gain and increase in net return are percentage increases over conventional practice, as reported in the cited studies. Percentage increase = [(CF value − conventional value) / conventional value] × 100. A dash (–) indicates that the corresponding value was not reported. '+' indicates percentage increase over conventional practices.

CF: customised fertiliser; N: nitrogen; P: phosphorus; P_2O_5: phosphorus pentoxide; K: potassium; K_2O: potassium oxide; Zn: zinc; B: boron; Ca: calcium; Mg: magnesium; S: sulphur; Fe: iron; Cu: copper; Mn: manganese.

Table 3. Influence of customised fertilisers on nutrient uptake by crops

Crop	Location	CF composition	Increase in nutrient uptake of crop							
			N (%)	P (%)	K (%)	S (%)	Zn (%)	Cu (%)	B (%)	References
Rice	Uttar Pradesh	100 % CF–N : P : K : S : Zn (12 : 26 : 18 : 5 : 0.5 %)	+6.53	+12.78	+4.60	+10.00	+2.45	-	+24.64	(17)
Rice	Chhattisgarh	100 % CF–N : P_2O_5 : K_2O : Zn (14 : 21 : 8 : 0.6 %)	+11.17	+11.92	-	-	+12.36	-	-	(24)
Wheat	Uttar Pradesh	100 %/ CF–N : P : K : S : Zn (12 : 26 : 18 : 5 : 0.5 %)	+15.52	+20.29	+15.51	+15.23	+15.22	-	+18.30	(25)
Maize	Tamil Nadu	100 % CF–N : P : K : Zn mixture	+43	+32.52	+44.77	-	+28.60	+34.27	-	(21)
Finger millet	Uttar Pradesh	100 % CF–N : P : K : S : Zn (20-17-11-3-0.4 %)	+46.19	+37.32	+30.9	-	-	-	-	(26)
Chickpea	Chhattisgarh	100 % - N : P_2O_5 : K_2O : S : Zn (11 : 27 : 0 : 6.6 : 0.5 %)	+8.16	+4.4	+3.89	+11.22	+6.19	-	-	(27)

Values are percentage increases in nutrient uptake over conventional fertiliser practices, as reported in the cited studies. Percentage increase = [(CF value − conventional value) / conventional value] × 100. A dash (–) indicates that the corresponding value was not reported.'+' indicates percentage increase over conventional practices.

CF: customised fertiliser; N: nitrogen; P: phosphorus; P_2O_5: phosphorus pentoxide; K: potassium; K_2O: potassium oxide; Zn: zinc; B: boron; Ca: calcium; Mg: magnesium; S: sulphur; Fe: iron; Cu: copper; Mn: manganese.

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Recovery efficiency (RE) is another important parameter that reflects the increase in nutrient uptake by the crop per unit of fertiliser applied. It can be computed by: RE (%) = (Nf-N0/Fa) × 100, where, Nf represents the nutrient uptake in the above ground biomass of the fertilized plot (kg), N0 denotes the nutrient uptake in the above ground biomass of the control plot (kg) and Fa is the amount of fertiliser applied (kg). The application of CF has been reported to improve recovery efficiency primarily due to reduced nutrient losses, lower fixation, correction of limiting micronutrient deficiencies and improved uptake efficiency per unit of nutrients applied (30).

Partial factor productivity (PFP) denotes the ratio of yield per quantity of added fertiliser, indicating how effectively the added nutrients contribute to production (kg kg^{-1}). Higher PFP values indicate better FUE and help in achieving higher yields with lower input costs. The use of CF results in higher PFP because they provide a balanced supply of nutrients and improve nutrient uptake by the crop. They also enhance the use of native soil nutrients and overall nutrient use efficiency, leading to more effective conversion of nutrients into grain yield (31).

An experiment conducted in Maharashtra on onion established that application of CF with a composition of N : P : K : S : Mg : Zn (20 : 12 : 10 : 4: 0.25 : 0.50 %) resulted in higher FUE compared to recommended dose of fertiliser (N : P_2O_5 : K_2O-100 : 50 : 50 kg ha^{-1}). The highest FUE (22.27 kg kg^{-1}) was recorded with CF, whereas conventional fertiliser showed lower efficiency (19.12 kg kg^{-1}) (32). The direct supply of micronutrients in balanced proportions helps maintain their adequate levels in the soil. Furthermore, split application ensures better synchronisation of nutrient release with crop demand, thereby reducing nutrient losses (33). The improvement in fertiliser use efficiency due to customised fertiliser application is presented in Table 4.

Contribution to crop yield and economics benefits

Customised fertilisers are considered an effective approach for meeting crop nutrient requirements and enhancing crop productivity (34–37). A soil test-based nutrient management strategy for rice, incorporating recommendations for lime application and balanced fertilisation with both macro- and micronutrients along with supplemental foliar nutrition during critical growth stages, was reported to improve crop productivity and profitability in the acid saline soils of Kerala (38). The use of CFs also improved crop growth and development (39). This improvement was attributed to the balanced supply of nutrients throughout the crop growth period, which prevented nutrient stress at different growth stages (40). Furthermore, the combined application of macro- and micronutrients enhanced biological N fixation, promoted plant growth, increased nodulation and supported better flowering, pod development and grain formation, ultimately resulting in higher chickpea yield (41). Similarly, the application of KAU Multimix Sampoorna, a micronutrient mixture containing Zn (4.2 %), Cu (0.4 %), B (3 %), Mo (0.015 %), Fe (0.15 %) and Mn (0.14 %), improved crop growth and yield in chilli and okra (42). This improvement was attributed to the adequate supply of essential nutrients during the crop growth period and its effectiveness in correcting multi-nutrient deficiencies, thereby serving as an immediate remedial measure (43).

The economic analysis of CFs revealed an increase in net returns and benefit–cost (B : C) ratio compared to conventional practices (44). The higher net returns and B : C ratio observed in CF-treated plots compared to recommended practices can be attributed to their ability to meet crop nutrient requirements in a site-specific manner, considering soil type and crop growth stages, thereby preventing nutrient deficiencies and enhancing economic returns. The improvement in crop yield and economics due to customised fertiliser application is presented in Table 5.

Economic feasibility and adoption trade-offs

Break-even conditions for CFs may vary considerably with farm size. Smallholders generally face higher soil-testing, procurement and transaction costs per unit area and therefore require a relatively greater yield or income advantage to recover the additional investment. Larger farms can spread these costs over a greater cultivated area and may also benefit from bulk procurement, thereby lowering the yield increase required to reach break-even. Hence, farm size should be considered when evaluating the economic viability and adoption potential of CFs (59). Break-even analysis of small vs. large farmers are presented in Table 6.

Table 4. Influence of customised fertilisers on fertiliser use efficiency

Crop	Location	CF composition	Increase in agronomic efficiency (%)			Recovery efficiency (%)			Increase in PFP (%)	Increase in PE (%)	References
			N	P	K	N	P	K	N	N	
Wheat	Karnataka	N : P_2O_5 : K_2O (14 : 17 : 17)	+72.63	+ 84.2	+121.3	34.42	24.52	115.23	-	-	(28)
Mustard	Bharatpur	100 %/ CF - NPKSZnB (15 : 15 : 15 : 9 : 0.5 : 0.2)	+56	+56	+56	45.14	-	-	+16.43	+7.96	(29)
Elephant foot yam	Kerala	N : P : K : Mg : Zn : B (7 : 12 : 24 : 3.5 : 1.25 : 0.4)	+27.1	+48.5	+90	-	-	-	-	-	(37)

'+' indicates percentage increase over conventional practices. CF: customised fertiliser; N: nitrogen; P: phosphorus; P_2O_5: phosphorus pentoxide; K: potassium; K_2O: potassium oxide; Zn: zinc; B: boron; Ca: calcium; Mg: magnesium; S: sulphur; Fe: iron; Cu: copper; Mn: manganese; PFP: partial factor productivity; PE: physiological efficiency.

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Table 5. Influence of customised fertilisers on crop yield and economics

Customised grade	Crop	Location	Yield gain (%)	Increase in net return (%)	Benefit cost ratio (%)	References
100 % CF – N : P : K : Zn (14 : 21 : 8 : 0.6)	Rice	Raipur	+9	+4.74	2.31	(44)
N : P : K : Zn	Rice	Tamil Nadu	+22	-	-	(45)
N : P : K : S : Zn : Mg (8 : 15 : 15 : 1 : 0.5 : 0.15)	Rice	Uttar Pradesh	+15	+15.87	3.01	(46)
100 % CF – N : P : K : S : Zn - (10 : 26 : 17 : 1.0 : 0.3)	Rice	Uttar Pradesh	+10	-	-	(47)
100 5/ CF – N : P : K : S : Zn : B - (10 : 18 : 25 : 4 : 0.5 : 0.2)	Wheat	Uttar Pradesh	+33	-	-	(47)
N : P : K : S : Zn	Wheat	Uttar Pradesh	+16	+4	1.89	(48)
100 % CF – N : P : K : S : Zn - (12:26 : 18 : 5 : 0.5).	Wheat	Uttar Pradesh	+18			(49)
100 % CF – N : P : K- (6 : 6 : 2)	Bajra	Rajasthan	+17	+12	2.49	(50)
N : P_2O_5 : K_2O : S : Zn (57.5 : 31.8 : 20.6 : 5.6 : 0.7 kg/ha)	Finger millet	Bangalore	+46	+79	2.35	(51)
N : P : K : S : Zn : Fe : B : Mo	Chickpea	Rajasthan	+15	+19.24	2.88	(41)
N : P : K : S : Zn : Mo	Chickpea	Manipur	+19	+59.76	1.28	(52)
N : P : K : S : Zn : Mo	Chickpea	Raipur	+20	-	-	(53)
Macro nutrients and micro nutrients	Cotton	Maharashtra	+14	-	-	(54)
N : P : K : S : Mg : Zn : B : Fe (20 : 10 : 10 : 5 : 2 : 0.5 : 0.3 : 0.2)	Pomegranate	Maharashtra	+10	-	-	(55)
N : P : K : Ca : Mg : S : Fe : Mn : Cu : Zn	Bitter gourd	Tamil Nadu	+26	-	-	(56)
N : P : K : Mg : B (22.01 : 3.35 : 12.68 : 5.97 : 0.37)	Okra	Kerala	+15	+11.52	-	(57)
N : P : K : Zn : B : S (150 : 67.5 : 97.5 : 3.75 : 0.37 : 22.5 kg ha^{-1})	Potato	Uttar Pradesh	+29	- +50.54	1.78	(58)

Yield gain and increase in net return are percentage increases over conventional practice, as reported in the cited studies. Percentage increase = [(CF value − conventional value) / conventional value] × 100. A dash (–) indicates that the corresponding value was not reported.'+' indicates percentage increase over conventional practices. CF: customised fertiliser; N: nitrogen; P: phosphorus; P_2O_5: phosphorus pentoxide; K: potassium; K_2O: potassium oxide; Zn: zinc; B: boron; Ca: calcium; Mg: magnesium; S: sulphur; Fe: iron; Cu: copper; Mn: manganese.

Table 6. Break-even analysis for small vs. large farmers

Sl. No	Aspect	Small and marginal farmers	Medium and large farmers
1	Soil-testing cost per unit area	Relatively high because testing costs are spread over a small area	Lower because costs can be distributed over a larger area
2	Procurement of CF	Small quantities may have higher transaction/transport costs	Bulk purchase can reduce unit cost
3	Advisory and diagnostic costs	Greater relative burden	Lower relative burden
4	Capacity to bear additional investment	Limited	Relatively greater
5	Risk of uncertain yield response	High because even a small loss can affect farm income	Better capacity to absorb seasonal risk
6	Break-even yield requirement	Generally higher	Generally lower due to economies of scale
7	Likely adoption	Depends strongly on assured yield and price advantage	More feasible when CF provides moderate but consistent benefits

CF: customised fertiliser.

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Regional cost implications

Developing CFs involves additional costs for soil sampling, laboratory analysis, GIS mapping, formulation and field testing. These costs may be lower in regions with established soil-testing facilities and reliable soil databases. In contrast, poorly mapped regions or areas with highly variable soils may require more sampling and analysis, increasing the cost of customisation. Therefore, the benefits of greater site specificity should be balanced against the additional cost of developing and validating customised fertiliser formulations.

Subsidy implications and policy recommendations

In India, CFs do not receive a separate subsidy at the point of sale, although manufacturers can use subsidised P and K fertilisers as raw materials under the Nutrient Based Subsidy (NBS) scheme. To improve their affordability and adoption, particularly among smallholders, policy support could focus on subsidised soil testing, development of regional soil fertility databases, field demonstrations and collective procurement through farmer organisations. Such targeted support could reduce the cost of customisation while promoting balanced and need-based fertiliser use (60).

Economic viability under different cropping systems

The economic viability of CFs varies across cropping systems because of differences in crop value, nutrient demand and yield response. Their use may be more profitable in high-value crops and intensive cropping systems, where increased yield and quality can compensate for the additional fertiliser cost. In contrast, their profitability may be lower in rainfed or low-value crops where yield responses are less predictable. Therefore, the economic suitability of CFs should be evaluated for individual cropping systems rather than generalised across crops (27).

Limitations and challenges

- Customised fertilisers face several challenges that limit their large-scale adoption and commercialisation. One of the major constraints is their high production cost, as manufacturing requires advanced technology, specialised infrastructure and substantial capital investment. In addition, fertiliser formulation depends on reliable soil and crop information; inadequate sampling or outdated soil-fertility maps can result in inappropriate grades. Because nutrient requirements vary spatially and temporally, a grade developed for one region may not perform similarly under different soil, climate, cultivar or management conditions.
- At the farmer level, limited awareness, low purchasing capacity and the comparatively higher price of CFs reduce their acceptance, particularly among small and marginal farmers.
- The formulation gaps of CFs for legume crops arise mainly due to the unique nutrient requirements and biological characteristics of legumes. Unlike cereals, legumes can fix atmospheric N through symbiotic association with rhizobia, reducing their dependence on external N fertilisers. Excessive N supply may also interfere with biological N fixation; therefore, customised grades for legumes need to account for soil N supply, symbiotic N fixation and crop-specific nutrient demand. Customised fertilisers can be environmentally beneficial if the right nutrients are applied at the right rate, time and place. However, inappropriate formulation or excessive application can still result in nutrient accumulation, leaching, runoff or gaseous N losses. Thus, customisation alone does not guarantee lower environmental impact; appropriate fertiliser rates, timing and application methods are also important.
- Greater emphasis should be placed on developing and supplying region-, agro-climate- and crop-specific customised fertiliser formulations to address deficiencies of secondary and micronutrients effectively. Such an approach could achieve better crop response, enhanced productivity and improved soil health when supported by accurate soil testing and appropriate application practices. Long-term field validation is required before broad environmental or sustainability benefits are generalised across regions.

2. Conclusion

Due to the underuse and overuse of fertilisers, nutrient deficiencies and toxicities have emerged in soils leading to reduced fertiliser use efficiency (FUE). Customised fertilisers (CFs) which supply macro and micronutrients in balanced proportions according to crop and soil requirements help improve nutrient availability, enhance FUE and increase crop productivity. Moreover, they contribute to reduced nutrient losses and improve environmental sustainability. Integration of CF with precision nutrient management approaches like site-specific nutrient management (SSNM) can further enhance their effectiveness. Therefore, wider adoption and policy support are essential to promote CF-based nutrient management in modern agriculture.

Research priorities and knowledge gaps

- Long-term studies are needed to evaluate the impact of CFs on soil health, soil microbial activity and nutrient dynamics under different cropping systems.
- Further studies are required to assess the efficiency of CFs under abiotic stress conditions such as drought, salinity and nutrient-deficient soils.
- Research is needed to understand the synchronisation between nutrient release patterns of CFs and crop nutrient demand at different growth stages.
- Detailed evaluation of the economic feasibility, farmers' adoption behaviour and large-scale commercialisation of CFs is required across diverse agro-ecological regions.

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Authors' contributions

SB conceptualised and designed the review topic. NS contributed to writing the original draft, review and editing, preparation of figures and tables and drafting of the manuscript. SPP, SRT, BNK, SP and SK were involved in drafting, reference collection, editing and correction of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the language. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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