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A Critical Review of Crop-Yield Data for Rice (*Oryza Sativa L.*) On Using Sri Lankan Biofilm Biofertilizers

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Abstract
The challenge of sustainable agriculture has generated a global interest in microbial fertilizers. A Biofilm-biofertilizer introduced in Sri Lanka is claimed to reduce the usage of chemical fertilizers (CF) by ~50% while boosting harvests of rice (Oryza sativa L.) and other crops by 20-30%. In contrast, biofilm biofertilizers tested elsewhere have usually given inconsistent results. Just prior to Sri Lanka launching "100% organic farming", the country had officially approved a nation-wide use of the commercialized biofilm-biofertilizer. Here we examine the available data on rice yields for the Sri Lankan biofertilizer and show in detail that the improved yields claimed fall within the usual uncertainties (error bars) of rice harvests. Theoretical models that produce a seemingly reduced CF usage with a misleading "increase" in harvests, as well as field data from several laboratories of the government department of agriculture are used to assess these claims. We find that Sri Lankan biofilm biofertilizers in current use have no discernable positive impact on rice yields or in reducing the need for mineral fertilizers. The field data suggest an estimated loss of at least 16 million kg in the rice harvest for 2017-18 due to BFLk use.

Keywords: Agro-Ecosystems, Biofertilizers, Biofilms, Crop Yields, Rice, Maize, Tea, Vegetables

1. Introduction

Current agricultural technologies face the challenges of feeding an increasing world population, climate degradation as well as socio-political uncertainties. Newer agro-technologies, e.g., no-till agriculture seek to preserve the soil ecosystem undisturbed, while recent microbial techniques attempt to harness the soil microbes to provide some of the nutrients, reducing the need for chemical fertilizers [1-8].

In a previous study entitled "A critical examination of crop-yield data on vegetables, maize (Zea mays L) and tea (Camellia sinensis L.) for Sri Lankan biofilm biofertilizers", the performance of a biofilm-biofertilizer (BFBF) implemented in Sri Lanka and referred to here as BFLk (Sri Lanka patent 15958) was critically examined for those crops [9].

The BFLk products claim to reduce the officially recommended amount (ORA) of chemical fertilizers (CF) by 50%, while boosting the yields by some 20-30% for most crops [11]. However, our study [9] of BFLK use with vegetables, maize and tea showed that BFLk had little or no impact on their harvests. This is in line with the difficulties noted by other workers in implementing biofilm biofertilizers, although some groups have reported success. More uniform success has been achieved in formulating biopesticides, e.g., using Trichoderma, for instance, against common soil pathogens like Rhizoctonia solani that affect Rice, Maize etc [8,9,12,13,14,15].

However, as regards biofertilizers that are uniformly effective over many crops and many climate and soil zones, the situation is less satisfactory. Even in 2016, scientists associated with the commercialization of BFLk had stated that only pot experiments were successful [10]. As other nations are also hoping to implement biofilm biofertilizers, details of the Sri Lankan exercise and its socio-political dimensions may help them avoid some of the associated pitfalls [16].

As rice (Oryza sativa L.) is the staple diet of Asia and Sri Lanka too, we focus on the use of BFLk and its claims for rice cultivation [11,17,18].

1. The use of BFLk enables a reduction of the officially recommended amount of chemical fertilizer by 50% while boosting rice harvest by 20-30% .
2. It improves the quality of the soil.
3. BFLk advocates have stated that independent studies conducted at the research institutes of the Department of Agriculture (DOA), Sri Lanka, have confirmed these claims.

Four months prior to the total ban on agrochemicals proclaimed for 100% organic-farming imposed in April 2021, the then government had approved the nation-wide use of BFLk by farmers. Other government organizations had supported the product since 2014 [11,18,19,20,21,22].

However, the Principal Agriculturist, DOA had called for more field trials before a national recommending BFBF. The Principal Soil Scientist, DOA had stated that "because of significant yield reduction", substitution of even 35% of recommended CF with BFBF is not advisable. Probably the DOA, being a government department had to agree to a limited approval 5in the context of the now-abandoned "100% organic" policy of the then government [23-26].

Our analysis, based on existing data from the literature, from field trials, and from theoretical models, leads to the following conclusions. (i) BFLk does not meet the claims made for it. (ii) The addition of BFLk has no impact on rice yields other than a general decrease in harvests. (iii) The officially recommended amount (ORA) of chemical fertilizer for rice, not specific to a location (NSL), is found to be too high when based on the results from Ambalanthota, Bathalagoda and Mahailluppallama, the three field stations of the DOA. In fact, 65% of the NSL-ORA of fertilizer appears to be sufficient when chemical fertilizers alone are used. We recognize that the Dept. of Agriculture has issued location-specific information booklets for the 24 districts of the Island modifying the ORA of chemical fertilizers for rice cultivation. However, BFLk advocates have used amounts in excess of the ORA (e.g., 425 kg/ha) as the reference ORA, justifying it as 'a common practice among farmers' to claim that using 50% of 425 kg/ha together with BFLk gives 20-30% more harvest, though no robust data in support of even this has been presented [18].

2. Methods

In this study we use a three-pronged approach, namely (i) review of existing data reported in the literature on claimed rice-yields obtained when using biofertilizers, (ii) comparing with actual field data from crop trials conducted at accredited laboratories, and (iii) the construction of theoretical models to provide generic crop-yield data, as well as maximum and minimum yields that may be expected.

2.1. Rice yields using CF and CF+BFBF.

A paddy field is a managed complex ecosystem (Fig. 1) involving land preparation, water and crop management. The harvest is determined by a complex interplay of many factors involving the cultivars and nutrients used, environmental effects, crop and pest management. The name "complex system" is used here in the technical sense that the behaviour of the system (e.g., the expected harvest) becomes non-predictable even though deterministic, unless it is managed properly [26].

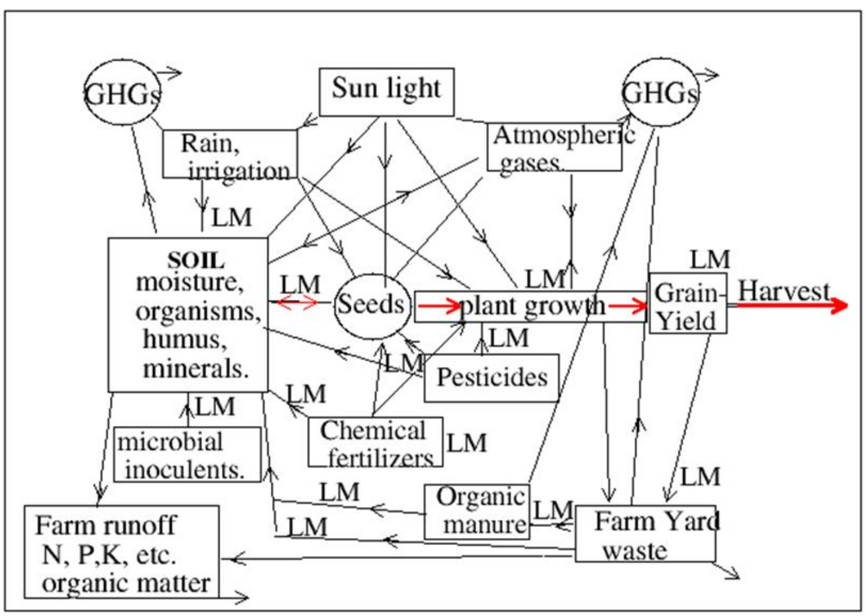


Figure 1: Rice cultivation as a managed complex ecosystem. The labels LM indicate labour, machines and management of soil, seeds, mineral fertilizers, organic and microbial inputs, pesticides, water and other inputs. GHG: green-house gases.

While the full complex system of Fig. 1 cannot be easily modeled, it is usual to model some aspects of it in the form of rice-yield functions Y(X1,X2,…) where Xi represent amounts of various inputs, e.g., fertilizer, labour etc. Since experimental yield functions have not been presented by BFBF researchers, we construct the expected rice yield functions using standard theoretical approaches. These will be complemented by field data as well.

3. Results

The main results of our investigation age given in section 3 where theoretical and experimental rice-yield functions are discussed. Section 4 deals with the response to variations in N, P and K.

3.1. Yield Functions for Rice Harvests

We consider (i) a model yield function used in publications of the International Rice Research Institute (IRRI), and (ii) Yield functions appropriate to the Sri Lankan rice-harvest data of Table 1, noting that Sri Lanka has a tropical climate through out the year with two planting seasons, Yala and Maha defined by two monsoon periods. (iii) Yield functions for the data of Premarathne et al 2021 [18]. (iv) Experimental yield functions specific to the localities of the DOA rice research stations.

A model-yield function (IRRI, Dawe et al 1997 [27]) is given by the relation:

$$Y\ [kg/ha] = 1163 + 19N + 0.06\,N^2 + 37P - 0.1P^2 + 23K - 0.09K^2 + 2.2S + 292I + 7.1M + 2.8L + c_1X + c_2X^2 + \ldots \quad (1)$$

In the above, N, P, and K are the recommended inputs in kg/ha of N, P and K while S and I are seed and pesticide inputs. The quantities M and L stand for mechanical (tractor), management and labour inputs in days [27]. Additional inputs X (e.g., Zn, Ca, S, or BFBF inoculants) can be included via terms like c_1X, c_2X^2, where c_1, c_2 are the linear and quadratic coupling coefficients for input X.

Season S	Years	Average Yield Y_A(geographic) from DCS	Mean Yield Y_m(temporal) $\frac{(S1+S2)}{2}$	Uncertainty U_T (Temporal) $\frac{(S1-S2) \times 100}{Y_m}$
Maha	2021/2022	2,860	3820[a]	50%
Maha	2020/2021	4,780		
Yala	2022	3,710	4470[b]	34%
Yala	2021	5,230		
***Data below cover the period studied by Premarathne et al 2021*[18]**				Uncertainty U_G (geographic) $\frac{(Max-Min) \times 100}{Y_A}$
Season	Year	Y (max, min)	Y_m	U_G
Maha	2018/2019	4750 (6620, 3210)	4525	71%
Maha	2017/2018	4300		
Yala	2018	4680 (6560, 3030)	4435	75%

[a]Average over two Maha or two Yala seasons. [b] % Difference over two Maha or two Yala seasons

Table 1: The average rice yields [kg/ha], maximum and minimum yields (for selected cases), mean values and percentage uncertainties, for years including those relevant to the study of Premarathne et al. Data are from the Dept. of Census and Statistics (DCS), Sri Lanka. There are two rainy periods (monsoons) and two planting seasons known as "yala", and "maha" covering 12 months [18,28]. The large variation in yields reflects the large variations in soils, rainfall and climate.

Using the conversions N=0.466×U, P=0.245×TSP, K=0.52×MOP, based on their chemical formulae, and CF=U+TSP+MOP, where U, TSP, MOP stand for appropriate amounts of urea, triple super phosphate and muriate of potash, respectively, we can rewrite Eq. (1) as a quadratic form up to second-order in the total input CF included.

$$Y[kg/ha] = a_0 + a_1[CF] + a_2[CF]^2 + \ldots \quad (2)$$

Here [CF] is the amount of CF in kg/ha used. In Eq. (2) higher-order corrections (beyond quadratic) that become important for CF inputs exceeding 100% CF by large amounts are neglected. As the BFBF procedure refers to using 50% CF, the use of a quadratic form is adequate. While the IRRI model is generic, the rice harvests reported in Table 1 can be directly used to construct country-specific yield functions for Sri Lankan data.

1	Specification	Urea N=46.6%	TSP P=24.5%	MOP K=52%	Total CF	Microbials
2	DOA-rain fed	175	35	50	260	---
3	DOA-irrigated	225	55	60	340	---
4	Premarathne et al (2021) 100% CF	284	76	66	425	---
5	Premarathna et al 2021, 50% CF + BFBF	300/2	80/2	70/2	450/2	2.5

Table 2: Fertilizer composition in kg/ha, specified by DOA and in Premaratne et al (2021) Microbials in Litres/ha

We give the coefficients for the Yala 2018 data, for rain-fed (260 kg/ha), irrigated (340 kg/ha) CF inputs respectively, and using the geographic average, maximum and minimum yields for the 2018 Yala season data in Table 3.

Model	a_0 [kg/ha]	a_1 [number]	a_2 [ha/kg]	100% CF [kg/ha]	Notes
IRRA with DOA CF	2077	7.101	-0.006014	260	N,P,K as per DOA. Row no. 1, Tab. 3
IRRA with Premarathne et al (2021) CF	2077	7.526	-0.005986	425	N, P, K per , Row no. 4, Tab. 3
IRRA with above, 50% CF, BFBF=0.	2077	7.514	-0.005980	450	Row no. 5, Tab 3
Yala-2018 rice data are used for SL data model					$Y_{100\%}$, $Y_{50\%}$, [kg/ha]
SL-DOA CF input	2000 [kg/ha]	20.62 [number]	-0.03964 [ha/kg]	260 [kg/ha]	4680, 4010
SL-Max. *Y*	2200	25.65	-0.03772	340	6560, 5470
SL-Min. *Y*	1800	9.462	-0.01820	260	3030, 2722
SL- Premarathna CF input. No. 4, Tab.3	2000	21.85	-0.03995	426	4058, 4842
Mahailluppallama Yala 2017	2181	1.911	-0.00951	315	Quadratic fit to DOA field data

Table 3: Coefficients for the rice yield functions defined by Eq. (2).

The coefficients of the IRRI model using the DOA recommendation (Table 2, no. 1) of CF, i.e., 260 kg/ha reduce to a_0=2077 kg/ha, a_1=7.1001, a2 = - 0.006014 ha/kg (Table 3). The constant a_0 contains the inputs from labour (L), tractor use (M) and management of soil, seeds (S), pesticides (I) etc., that we do not elaborate in detail as they have not been reported in the rice experiments with BFBF. So, any typical combination of them (kept constant) that gives a yield of about 2000-3000 kg/ha, typical of harvests without any fertilizer application, is sufficient for our purpose.

The last row of Table 3 gives the coefficients of the quadratic model that fit the location-specific field data for the yield function Y(X) obtained from field trials at the Field Crops Research & Development Institute, DOA, Mahailluppallama during the 2017-Yala season where X is the chemical fertilizer input (no BFBF). It is seen that the coefficients are, grosso modo, of the same magnitude, confirming the applicability of the model. These models are used to establish maximum and minimum yield curves indicating the range of uncertainty in the data.

The DOA rice-harvest data from field trials are discussed below.

3.2. Results DOA Field Trials on Rice Using CF Alone and With CF And BFLk

The field stations are located at Ambalanthota (A), Bathalagoda (B) and Mahailluppllama (M). The results from the Rice Research & Development institute (RRDI) of the DOA are available for the Yala season of 2017 from all three field stations A, B, and M, while results for the Maha season 2017/2018 are available only for the location B. One of the present authors (Sumith A) was a full collaborator in these field trials (although not employed by the DOA at the time of these trials, but in his capacity as a former Director of the RRDI of the Department of Agriculture). More details of these field trials and additional data sets are given in Appendix A [23,24].

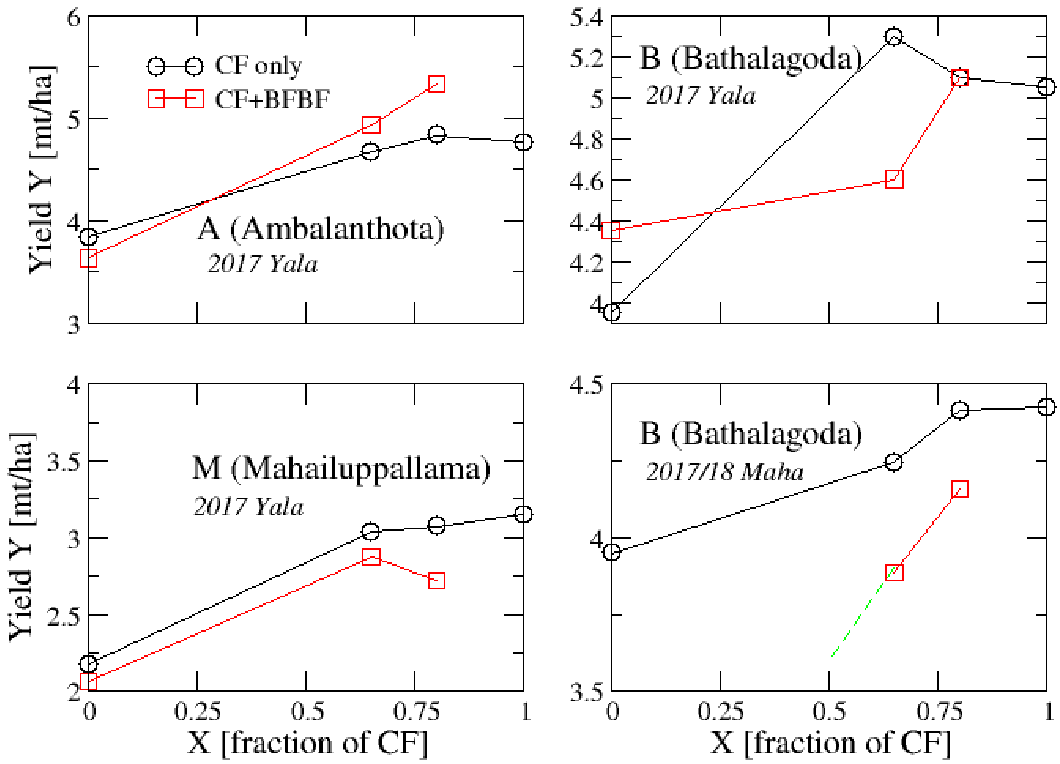


Figure 2: Rice yield data (dry weight of grain) obtained using various fractions X of the recommended DOA amount of CF only (data points with circles), and with CF+BFLk, (data points with squares) obtained from field trials at the DOA research stations as indicated in the panels. Bathalagoda data are available for both the Yala 2017 and Maha 2017/18 seasons. The yield at 50% CF+BFBF is what is relevant to the major claim of BFLk advocates. This can be read off from the graphs.

The four panels of Fig. 2 display the rice yields [mt/ha] obtained for various treatments (T) using varying amounts of chemical fertilizer, expressed as X = (kg/ha of CF used)/(DOA recommendation) and plotted along the x-axis. The effect of adding BFLk is seen to decrease the rice yields in general, a fact noted by DOA scientists in their submissions to the agricultural ministry. The variations in the yields among the three research sites A, B, and M show the significance of location (L) effects in these studies. However, in the statistical analysis of the treatment (T) and the location (L), the T× L interaction effect was found to be not significant at 5% probability level, so that different treatments responded in the same manner with different environments. This justifies the comparison of treatment averages over the environments covered by the three research stations. What is noteworthy is that BFLk fails to perform even within this set of environments. Hence, claims that it works for the much more diverse set of 24 districts of the whole island, as based on farmers' experience, is farfetched.

As the claims of BFLk refer to the use of at least 50% CF complemented by BFLk, the field trials adequately cover the relevant regime. We note a large decrease in harvests when BFLk is used, in all cases except for Ambalanthota. However, the change of 2% in the harvest when 50% of CF+BFLk is used (4.6 mt/ha), as compared to CF only (4.5 mt/ha) is not significant.

Using the yields at 50% CF with and without BFLk, and averaging over the four sets of trials at A, B and M, an overall decrease of about 7.5%-7.8% in rice yields is found for BFLk +50% CF use. From Table 1, the average yield Y_m is 4480 kg/ha over 2017-2018. Hence, assuming a 16% market penetration of BFLk among Sri Lankan farmers, and assuming that 300,000 hectares were harvested per year in 2017-2018, the total estimated loss in the national rice harvest due to BFLk use is about 16 million kg of rice per annum.

These results confirm, for rice harvests as well, the negative conclusions found in Ref. for BFLk usage for vegetables, maize and tea [19].

DOA field trials are also available where the effect of adding BFLk on N, P, and K are individually assessed. We review them after a discussion of the publications by Premarathne et al, and Rathnathilaka et at 2023 [18,21].

3.3. Biofertilizer Studies of Rice Yields By Premarathne et al

Premarathne et al claim to have studied 37 different locations and confirm a 50% reduction in CF usage as well as a 25% increase in harvests when using 50% CF+BFBF, as compared to 100% CF alone, but the relevant data have not been made available in the public domain. This claim is surprising in the light of the results of DOA trials conducted by RRDI scientists with no links to the commercialized product, using well-established methods in rice research

The optimal amount of CF that should be used in different sites should be site specific as recommended by the Dept. of Agriculture. The expected best harvests from different locations are also expected to vary significantly. However, Ref, uses a single prescription for the 100% CF to be used. We construct theoretical yield curves calculated within the IRRI model for the DOA recommended CF-alone application, and as used in Ref. These are shown in Fig.2(a), while Fig. 2(b) displays the yield functions based on actual Sri Lankan Yala 2018 data. The IRRI model is a generic model (not specific to Sri Lanka) that we use mainly as a reference model for this type of study.

In Table 1 we show details of (i) the geographic-average harvests (i.e., yields in kg/ha) denoted by Y_A, as reported by the Dept. of Census and Statistics (DCS) of Sri Lanka, (ii) the maximum and minimum yields for the Yala (2018) and Maha (2018-2019) seasons as they pertain to the period covered by Premarathne et al [18]. The data are rounded to the nearest 10 kg/ha.

The data show a temporal (season-dependent) variation in yields (harvests) that may reach 50%, while the geographic variation may reach 71%. Given such large variations, the claim that using 50% of required CF, together with BFBF leads to a 25% increase in the harvests (irrespective of location, season, crop type etc.) is of little value. Such an "increase" (or decrease) is well within the error bars (uncertainties UG and UT) indicated in the Table.

A further difficulty arises with Premaratne et al using 425-450 kg/ha as a substitute for the officially recommended amount (ORA) of CF per hectare when CF alone is used (100% CF), justifying this by stating that most farmers use far more CF than the ORA. Premarathne et al state that: "The treatments of the present study were (a) BFBF practice: 2.5 L of BFBF with 225 kg CF/ha (Urea 150, TSP 40 and MOP 35, kg/ha)], and (b) Farmers' practice [425 kg CF/ha (Urea 284, TSP 76 and MOP 66 kg/ha)]". However, the use of 225 kg/ha mentioned here as the 50% CF rate used with four different rice-growing regions implies the possible use of 450 kg/ha as the substitute for 100% ORA [18].

Depending on the type of cultivation, irrigated to rain-fed, the ORA at 100% CF are 305-345 ka/ha, and 225-265 kg/ha respectively, where the range of 40 kg allows for some site-specific variations. The different specifications are summarized in Table

Although Ref, [18] mentions field trials with 0, 65%, 80% and 100% of CF, and with BFBF, the obtained yields have not been reported. Other workers who have used BFLk have also not provided yield functions giving the rice yield (harvest/ha) as a function of fertilizer + BFBF inputs. So we use theoretical yield curves calculated within the IRRI model in our analysis.

Fig. 3(a) shows that just the increased CF usage (425 kg/ha) reported in Ref. [18] in their field trials would give a significant increase over the DOA CF value (e.g., 260 kg/ha or 340 kg/ha) if the IRRI model is used for prediction. Fig. 3(b) displays the yield curves obtained from the quadratic form based on the Yala 2018 rice yield data. The curve labeled "2018 Yala Av. Yield" corresponds to the theoretical yield function for a 100% CF input of 260 kg/ha, giving an average yield $Y_{100\%}$ of 4680 kg/ha. This average is taken over all geographic locations, where the maximum-yield location had a $Y_{100\%}$ of 6560 kg/ha, while the minimum-yield location has $Y_{100\%}$ of 3030 kg/ha. These enable us to construct the max. and min. yield curves which serve as the limits of the geographic (i.e., location to location) variation in the rice yield. The yield function for a CF input of 425 kg/ha, with the Urea, TSP and MOP proportions as use in Ref. [18] for the Sri Lankan model is displayed as the dot-dashed curve and shows that the higher CF input leads to a higher yield, as expected.

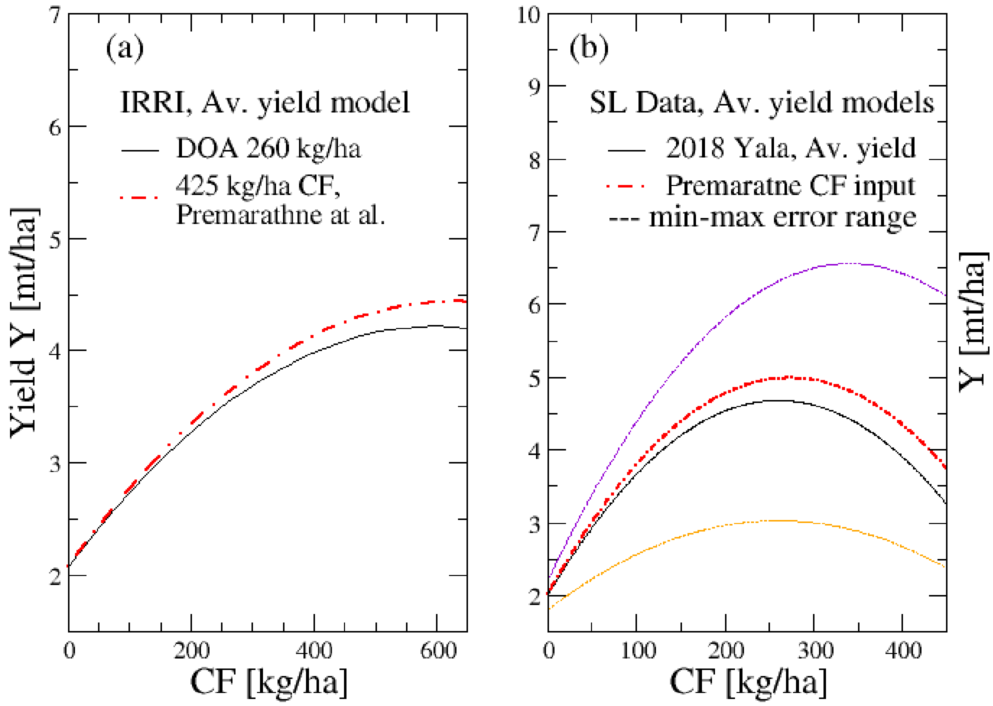


Figure 3: (a) The IRRI rice yield function of Dawe and Dobermann obtained with the DOA recommended CF input, and with the Premarathne et al CF input. (b) The yield functions constructed using the 2018 Yala harvest data (Table 2). The dotted curves define the two extremes (maximum and minimum) in geographic variation of the yield.

The DOA field trials showed that the use of BFLk had no substantial effect, and that on the average, its use reduced the yields. In Fig. 4 we display the yield curve for Sri Lankan data using the inputs of Ref. [18], already shown in Fig. 3(b), now assuming that the BFBF component added has no effect. The harvest at 100% CF only, viz. $Y_{100\%}$ = 4058 kg/ha corresponds to point A. We "throwback to point B, at 50% CF and have obtain a harvest $Y_{50\%}$ of 4842 kg/ha and hence may claim that the 50% CF+BFBF harvest is some 20% more than when 100% CF alone is used. This is purely a consequence of CF 100% being located in the non-linear decreasing range of the yield curve, but possibly interpreted by the advocates of BFBF as indicating the effectiveness of BFBF.

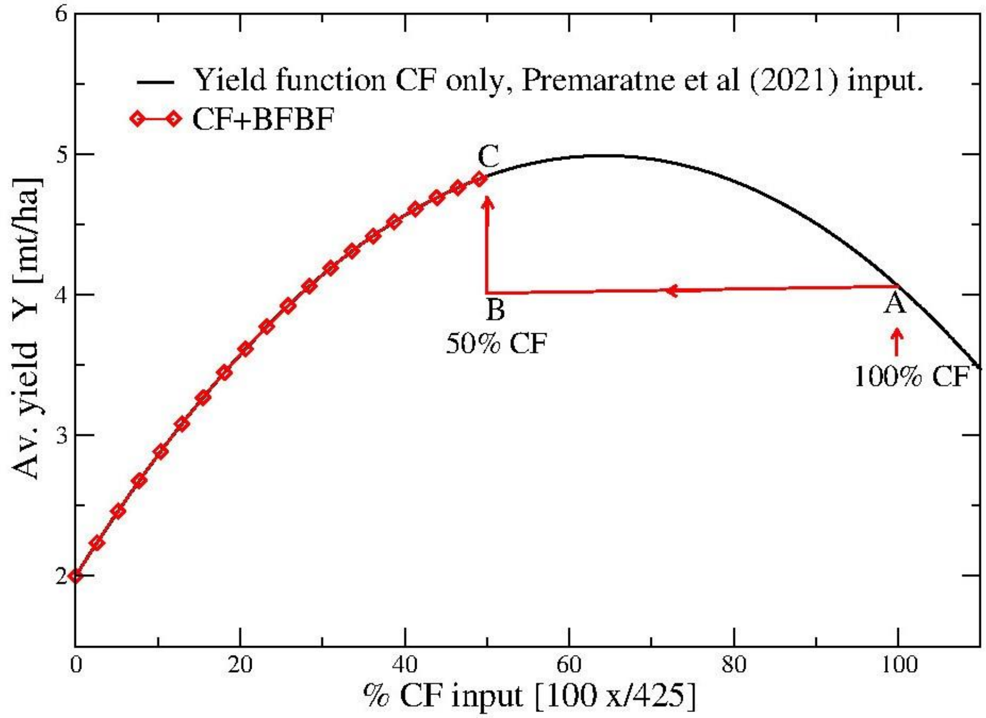


Figure 4: The yield function of Premarathne et al and their 50% CF+BFBF yield, (with zero contribution to the yield from BFBF) can be seen as a throw-back from the non-linear decrease that occurs near 100% CF application. Here, for simplicity we have used the specification of Ref. [18], line no. 4 of Table 3, which uses 425 kg/ha for CF+BFBF, while Ref. [18] has actually used slightly more CF in their BFBF procedure, viz., 50% of 450 kg/ha at point C in the figure.

Note that Premaratne et al have used higher levels of urea, TSP and MOP contributing to 225 kg/ha in their 50% CF+BFBF trials. This slight increase in chemical inputs may further bring the estimated 50% CF+BFBF harvest to 25% more, rather than the 20% estimated in the previous paragraph. Thus, the theoretical modelling clarifies how the apparent boost of harvests claimed by the BFBF practice is actually consistent with the BFBF having no effect [18].

The increased urea and other inputs, as seen in line no. 5, Table 2, are a likely reason for the increases of total grain weight and endophytic non-diazotrophs that were observed in Ref. [18] in the BFBF practice over the farmers' CF practice.

3.3. Effect of Using BFBF on N, P, and K Availability to The Rice Crop

In Rathnathilaka et al 2023 [21], the authors have used a soil quality index (SQI) and a sustainable yield index (SYI) to analyse their field-trials data. They state that "the soil total nitrogen (STN), soil total phosphorus (STP), soil potassium (SP), microbial biomass carbon (MBC) and soil fungi (SF) of the BFBF practice were significantly higher than that of the farmers' CF practice …. This clearly shows that excessive CF NPK that is not taken up by the plants in the BFBF practice is incorporated in to the microbial biomass, …".

This would presumably lead to an increase in yields, and reduced-NPK release to the environment. However, the NPK taken up by the microbes (included in estimated totals) are not available to the plants to increase yields. Rathnathilaka et al give in their Table 2, the percentage STN via BFBF and CF-alone practices as STN (%) 0.96, 0.44, i.e., an increase exceeding 200% in soil nitrogen, and similar large increases in SP and STP, but the claimed crop-yield increase is 25% is based on using an inflated ORA of 425 kg/ha. So, according to our analysis, it is a "throw-back effect" as illustrated in Fig. 4.

Furthermore, the enhanced microbial biomass now provides a new mechanism for releasing nitrogen and carbon to the environment in the form of green-house gas emissions. Nitrous oxide emissions from microbial techniques have been noted by Sabba et al, and Baggs. Furthermore, data on carbon dioxide emissions are not available [29,30].

The increased pH observed with the BFBF procedure, largely responsible for enhancing the STP and SP will correspondingly increase the levels of metal toxins like Cd, Pb, Hg etc., by releasing them from their soil-fixed states. In fact, cadmium and arsenic had figured in discussions of the etiology of some chronic diseases associated with geochemistry [31]. Hence studies on BFBF procedures should be accompanied by a heavy-metal assay of the soil.

A regression analysis shows that the SQI was significantly related with rice yield in the BFBF practice, unlike for farmers' CF practice. However, the objective of the farmer is not feeding the microbial biomass in the soil. While soil organic matter and microbial biomass are closely linked, their optimization has to be taken in the larger context of Fig. 1 where decreased external inputs, decreased GHG emissions, and increased harvests are the objective. In fact, using slow-release fertilizers synchronized with plant growth, one may avoid unnecessary microbial biomass increases as well as fertilizer run off [21,32].

Furthermore, in the BFBF practice using BFLk, 50% of the NPK inputs were supplied externally. Hence, we are dealing with a driven (i.e., a constrained) system for which the factor group analysis (eigenvector analysis) used to construct principal components may not apply, and the relevant matrices that are input for diagonalization are not shown to have the properties needed (symmetry of the matrix or hermiticity) for casting into a diagonal representation.

3.4. Data from DOA field trials on N, P, and K Availability When Using BFBF.

The DOA field trials use more standard methods than those used by Rathnathilaka et al [21] to determine the effect of adding BFBF to the soil and the impact of BFBF on N, P, and K availability and report yield data. The N, P, and K inputs are varied individually in the DOA trials, to obtain grain-yield curves [23-24]. We present the relevant results in Table 4, where A, B, and M indicate the locations Ambalanthota, Bathalagoda and Mahailluppallama.

Location →	**A *Yala* 2017**		**B *Yala* 2017**		**B *Maha* 2017/18**		**M *Yala* 2017**	
Treatment 100% PK	CF only [mt/ha]	CF+BFBF [mt/ha]	CF only [mt/ha]	CF+BFBF [mt/ha]	CF only [mt/ha]	CF+BFBF [mt/ha]	CF only [mt/ha]	CF+BFBF [mt/ha]
0% N	3.67	--	3.95	--	2.64	-	2.34	--
80% N	5.17	4.33	5.30	5.57	4.00	4.57	2.80	3.17
Treatment 100% NK	CF only	CF+BFBF	CF only	CF+BFBF	CF only	CF+BFBF	CF only	CF+BFBF
0% P	4.67	--	5.10	--	n. a.	n. a.	2.93	--
80% P	4.33	4.83	5.45	5.10	n. a	n. a.	2.96	3.43
Treatment 100% NP	CF only	CF+BFBF	CF only	CF+BFBF	CF only	CF+BFBF	CF only	CF+BFBF
0% K	4.23	--	5.15	---	n. a.	n. a.	3.56	--
80% K	4.00	4.40	5.40	4.70	n. a.	n. a.	3.55	3.16

Table 4 Yield data for rice on individually varying the N, P, K content of the chemical fertilizer used, with and with the biofilm-biofertilizer BFLK, from trials at three DOA research stations in Sri Lanka. Only results for varying the N input are available for the Maha season of 2017/18.

These results indicate that the use of BFBF may have, at best a marginal impact in regard to N and P availability, but perhaps none for potassium. Even in the case of N, an element assimilated by symbiotic microbes, the improvement in the yield at Bathalagoda (Yala 2017) at 80% N is only 5%, while the improvement at Mahailluppallama is 13%. In contrast, the yield drops by 16% at Ambalanthota on including BFLk in the treatment. Effectively, the mixed results obtained by other workers in other parts of the world are similar to these conflicting outcomes.

Positive NPK responses have been observed with microbial inoculants used in Columbia for cassava [14]. In contrast to BFLk, they find that the Columbian inoculants are most effective at low inputs of CF, and decline in effectiveness at high CF inputs. This is essentially the theoretically expected outcome for microbial behaviour in soils.

The DOA results (Table 4) do not support the strong claims made for the use of BFLk in rice cultivation. As already noted, grain yield of rice did not respond to added P and K at all indicating that added P and K is not essential for rice cultivation definitely for one season, and possibly more [33]. However, grain yield of rice responded only to added N only up to 80% of the recommended level while BFBF has no influence on the grain yield of rice at any level of N, P and K, indicating that BFBF cannot be a supplement for any of the N, P and K nutrients in rice. Even application of 65% of the recommended level of NPK did not reduce grain yield of rice in all three locations indicating that application of 65% of the recommended level of N is sufficient for rice.

4. Discussion

Rice cultivation is globally practiced under a wide variety of climatic conditions that vary from subtropical to tropical regions as well as elevations up to 2000 m above sea level. According to the theoretical maximum yield potential of rice is circa 23-24 mt/ha, while the highest yields reported so far, viz., 17 mt/ha, is from northern China. The highest rice yield from Sri Lanka, reported by seems to be 11.73 mt/ha, while ordinary outputs (national averages) are about 4-5 mt/ha. Hence there exists a yield gap of over a 500% for ordinary outputs! Given the need to conserve biodiversity, mitigate climate degradation and increase forest reserves, methods that maximize yields while reducing the farmed-land area are a priority [34-36].

We have not attempted to connect the yield functions to the crop growth-rate (CGR) function which links more closely with the biotic and abiotic factors affecting rice harvests depicted in the managed complex system (Figure 1). Soils subject to heavy monsoonal rains are constantly leached and are less fertile; the rice soils are exploited intensively, with continuous double cropping, with no fallow period [37]. The higher temperatures prevalent in Sri Lanka's rice growing regions ensure that organic matter decompose rapidly affecting soil biological properties and the cation exchange capacity. The injection of microbes into the soil via biofertilizers increases this decomposition. So, unlike in temperate soils with slow microbial activity and slower decomposition of organic matter the assumption that biofertilizers would work in favour of agriculture, rather than in favour of some soil microbial forms dominating, with corresponding increased green-house gas emissions must be considered. In effect, managing soil microbial populations is more difficult than managing purely inorganic inputs designed for time release according to field-determined CGR data [1,38].

The optimization of interactions among the soil microbiome and the plant roots is critical for microbial fertilization methods. These interactions are enhanced by the formation of biofilms that are a matrix of extracellular polymeric substances containing polysaccharides, proteins and lipids. Such biofilms are essential in some cases for successful root colonization [39]. However, neither cereal-crop variants showing increased biological nitrogen fixation, nor uniformly successful biofilm techniques have been reported for rice, except for BFLk whose claims are disputed in the present study. In fact, given these setbacks, genetic modification of flavone biosynthesis pathways in rice has been proposed as a general strategy to enhance biofilm formation of soil diazotrophic bacteria [40].

5. Conclusion

We have reviewed the data available on rice yields in Sri Lanka that can be obtained using various treatments that involve the use of a biofilm bio fertilizer (BFLk) that has been commercialized since 2010 and patented in 2013. This product, backed by the National Institute of Fundamental studies of Sri Lanka had won the patronage of the President of Sri Lanka and his advisors on agricultural policy in 2017, as one may conclude from newspaper reports [19]. Currently, the government of Sri Lanka continues to support it, opening manufacturing facilities for the BFLk product [41].

We estimated, using field data from three DOA research stations for 2017-2018, and a 16% market penetration of BFLK that the use of BFLk should have led to a decrease of the total national rice harvest by about 16 million kg/annum. The claims made for BFLk use, that it cuts down the need for chemical fertilizers and also boosts yields, could not be substantiated.

At a time when all agricultural products from fertilizers to pesticides are coming under increasing concern for their unforeseen environmental outcomes, their safety as well as effectiveness, all countries must learn from each other to avoid potential pitfalls and follow transparent evidence-based procedures. While the BFLk product does not meet its marketed claims, the associated scientific effort may have produced a group of scientists actively working in microbial fertilizers - a positive asset to be suitably deployed for further research and development .

Appendix A

In this appendix we present more details regarding two items.

1. More details of results of the Bio Film Bio Fertilizer (BFBF) trials, using as example the results from trials conducted in one season (Yala 2017) in three research stations of the Dept. of Agriculture are given below. These complements the graphical data in Fig. 2 of the main text.
2. Comment on the claim of BFLk scientists that the NIFS scientists associated with the commercial product have conducted satisfactory trials jointly with the DOA rice research institutes, although these results have not been made public.

• Item:1

An example of data analysis of field trials conducted in one season (Yala 2017) in three research stations of the Dept. of Agriculture is given below.

TRTMENTS (T)	Ambalantota		Batalagoda		Mahailuppallama	
	REP1	REP2	REP1	REP2	REP1	REP2
T1- NPK 100%	4.80	4.50	5.22	4.92	2.90	3.40
T2- NPK 80%	4.50	4.50	5.38	4.76	2.75	3.40
T3- NPK 80% + BFBF	4.50	5.50	5.84	4.38	2.27	3.17
T4- NPK 65%	5.00	4.50	5.68	4.92	3.00	3.08
T5-NPK 65%+ BFBF	4.30	4.50	4.84	4.38	2.75	3.00
T6- NK 100% +P 0%	4.50	5.00	5.61	4.61	2.45	3.40
T7- NK 100% +P 80%	4.50	5.00	5.99	4.92	2.83	3.08
T8- NK 100% +P 80% + BFBF	5.00	5.00	5.84	4.38	3.22	3.65
T9- NP 100% + K 0%	4.20	4.00	5.15	5.22	3.90	3.25
T10- NP 100% + K 80%	3.50	4.50	5.84	4.99	3.45	3.65
T11- NP 100% + K 80% + BFBF	4.30	4.10	5.53	3.92	3.13	3.20
T12- KP 100% + N 0%	3.00	4.00	4.76	3.15	2.17	2.50
T13- KP 100% + N 80%	5.00	5.00	5.38	5.22	2.53	3.07
T14- KP 100% + N 80% +BFBF	4.50	4.50	6.37	5.07	3.20	3.15
T15- NO FERTILIZER	4.00	4.00	3.99	3.92	2.23	2.13
T16- BFBF ONLY	3.40	4.00	4.69	3.99	1.75	2.38

Table 5: Grain yield (t/ha) of rice under different treatments of the BFBF trial conducted in three research stations of the Dept. of Agriculture in Yala 2017.

Treatments (T), Ambalantota, Batalagoda and Mahailluppallama are three locations (L) where the experiment was conducted and reps (R). In the analysis T= Treatments, L=Locations, R(L)= Reps within locations, T*L=T x L Interaction and E= Experimental error. The acronym GLM represents "general liner model" in regression analysis. Other acronyms follow the standard usage of statistical methods and data analytics, e.g., see UCLA statistical consulting group [42].

Analysis of data
The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	97.6609750	1.9532195	16.62	<.0001
Error	45	5.2883875	0.1175197		
Corrected Total	95	102.9493625			

R-Square	Coeff Var	Root MSE	Y Mean
0.948631	8.342181	0.342811	4.109375

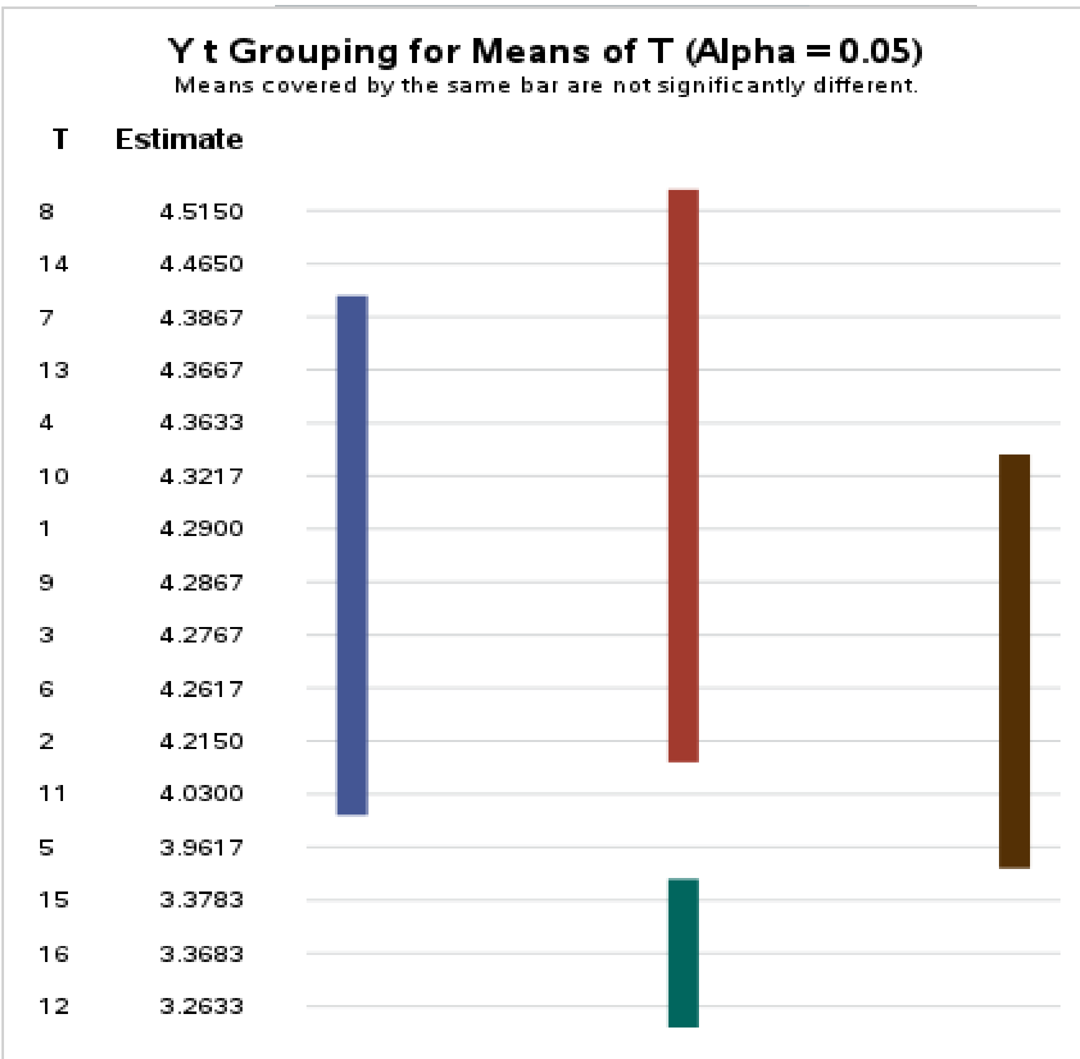
Source	DF	Type I SS	Mean Square	F Value	Pr > F
L	2	70.43222500	35.21611250	299.66	<.0001
T	15	14.98509583	0.99900639	8.50	<.0001
R(L)	3	6.75781250	2.25260417	19.17	<.0001
L*T	30	5.48584167	0.18286139	1.56	0.0879

The GLM Procedure

t Tests (LSD) for Y

Note: this test controls the Type I comparison-wise error rate, not the experiment-wise error rate.

Alpha	0.05
Error Degrees of Freedom	45
Error Mean Square	0.11752
Critical Value of t	2.01410
Least Significant Difference	0.3986



Treatment X Location interaction was found to be not significant at 5% probability level so that different treatments responded the same to different environments. This allowed to compare treatment averages over environments. No Nitrogen, nor fertilizer but only application of only BFBF treatments recorded the lowest grain yield. Grain yield of rice did not respond to added P and K at all indicating that added P and K is not essential for rice cultivation definitely for one season. However, grain yield of rice responded only to added N only up to 65% of the island-wide officially recommended amount (ORA) so that the application of 65% of the recommended level of N appeared sufficient for rice in all three locations. This shows that instead of the island-wide ORA, district specific ORA values must be used. Furthermore, far from being applicable in an island-wide sense, the BFBF protocol failed even within the spectrum of climate and soils covered by the three research stations. Even application of 65% of the recommended level of NPK did not reduce grain yield of rice when compared to that of 100% of the recommended level in all three locations. This was because rice responded only up to 65% of the recommended level of N while no response was observed for K and P at all. BFBF has no influence on grain yield of rice at any level of N, P and K indicating that BFBF cannot be a supplement for any of the N, P and K nutrients in rice.

• Item: 2

The claim that NIFS scientists and DOA scientists have confirmed boosted harvests and reduced CF inputs on using BFLk commercialization using trials on framers' fields.

Results from the three well established research laboratories of the Department of Agriculture (DOA) at Ambalanthota (A), Bathalagoda (B) and Mahailluppallama (M), discussed in item 1 and in the main text are an important part of our demonstration that the use of BFBF reduces crop yields. Authors Mahesh Premarthna (MP) and Gamini Seneviratne (GS), in responding to our manuscript have displayed the crop-yield curve from the Bathalagoda RRDI and say that the crop-yields are "insensitive" to fertilizer inputs, where as their graph itself shows that when the input of the NPK mineral fertilizer (MF) is increased from 0% to 60%, the harvest also increases by some 60% (i.e., from 2.6 t/ha to 4.2 t/ha). This includes the 50% range that BFBF is said to use and give a boosted harvest. However, at 50%, the harvest obtained when used together with BFBF is significantly LESS than that when NPK alone is used at 50%. This trend is established at other levels of fertilizer application and at other research stations as well, as discussed in detail by us [43].

So, although the yield-data are highly sensitive to fertilizer application in the 50% range, MP and GS claim that the data should be discarded because it is insensitive at the 64% and higher range. However, such insensitivity is exactly what is expected from crop-yield curves when they approach their turning points and their asymptotic regimes, as explained in this work as well as in a preceding manuscript where the failure of BFBF with respect to vegetables, maize and tea cultivation is documented. So, when authors MP and GS choose to ignore the results of the three DOA research stations, this may amount to cherry-picking data that fit their pre-conceived notions [9].

In fact, MP and GS claim that data their claims are based on "district-level" trials using farmers' fields, in association with DOA scientists and NIFS. Unfortunately, they do not disclose the names of the scientists who conducted the trials, and if they had any conflicts of interest in regard to the commercialized product. Furthermore, they have refrained from putting their data in the public domain. We invite them to display at least a minimal set of data that are needed to vindicate their longstanding (decade-old) claim for which not a single set of supporting data has so far been published, since 2010, other than conference abstracts or communications that provide inadequate information.

They claim to prefer results based on field trials conducted in farmers' fields, presumably under their substantive direction, rather than those of the research institutes. However, scientists at the government Rice Research and Development Institutes (RRDI) who have no commercial interest in the BFBF product were not satisfied with the uncontrolled and subjective procedures used. The name of the National Institute of Fundamental studies (NIFS) has also been invoked. The coordination of the NIFS with RRDIs was very poor, and farmer's trials were judged to be unreliable. The uniformity of such trials was not up to levels acceptable to the DOA. The RRDI collaboration was not sought in the statistical analysis and review of the data. Multi-locational trials conducted to test BFBF in farmers' fields were within-location, non-replicated and no evidence has been adduced to show that the farmers' field trials have been statistically analyzed using available well-tested statistical methods. Their analysis and interpretation of multi-locational farmers' field trials of BFBF appeared to be highly subjective and have not been made available for public scrutiny either via annual reports of the NIFS or via peer-reviewed publications.

It is evident that, based on scientifically conducted RRDI trials that are currently available in the public domain, the application of BFBF has no effect at all on either reducing the level of recommended fertilizer or boosting the yield of rice. The "justification" used by Seneviratne et al for recommending their commercialized BFBF for rice since at least 2014 is totally based on field trials conducted in farmers' fields that do not appear to meet the basic standards of rice research, while ignoring the more robust data that fully contravene their claims. It is unfortunate that COSTI, NIFS, and the government ministries subject to political forces have not used a scientific approach to decision making in approving products for use by farmers.

Other recent studies by independent scientists at universities also show that the use if BFBF in rice cultivation does not give increased harvests. Instead, BFBF procedures give reduced harvests for additional expense and increased work [44].

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