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# Exploring the potential to improve energy saving and energy efficiency using fertilizer deep placement strategy in modern rice production in Bangladesh

**Sanzidur Rahman**

School of Geography, Earth and Environmental Sciences, University of Plymouth, UK

**Basanta K. Barmon**

Department of Economics, East West University, Dhaka, Bangladesh

**Address for correspondence**
Dr. Sanzidur Rahman
Associate Professor in Rural Development
School of Geography, Earth and Environmental Sciences
University of Plymouth
Drake Circus
Plymouth, PL4 8AA
Phone: +44-1752-585911
Fax: +44-1752-585998
E-mail: srahman@plymouth.ac.uk

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# Exploring the potential to improve energy saving and energy efficiency using Fertilizer Deep Placement strategy in modern rice production in Bangladesh

## Abstract

*Nitrogen (N) fertilizer plays an important role in modern rice production and is required in large amount because it is the most limited nutrient as well. The Fertilizer Deep Placement (FDP) strategy is developed to improve efficiency of N fertilizer use and rice productivity. The present study estimates the extent of energy saving, productivity and efficiency impacts of FDP strategy in modern rice cultivation at the farm-level in Bangladesh using a stochastic production frontier approach. A total sample of 200 rice farmers (100 FDP users and 100 conventional urea users) from a village of Jessore district is utilized. Results reveal that FDP strategy significantly improves energy balance, energy ratio, energy productivity and technical energy efficiency. Relative gains are higher for Boro (dry winter) season than the Aman (monsoon) season. The key policy implication is that a widespread diffusion of FDP strategy should be pursued with priority as it holds the potential to significantly reduce energy use from a scarce, finite and renewable resource (i.e., urea fertilizer) while supporting growth in rice based agriculture of Bangladesh. Government should also support entrepreneurs to invest in briquetting urea into Urea Super Granules (USG) in order to effectively improve uptake of FDP strategy nationwide.*

**Key words:** Fertilizer Deep Placement (FDP) strategy, Urea Super Granules (USG), energy productivity, technical energy efficiency, stochastic production frontier, modern rice, Bangladesh.

**JEL Classification:** O33, Q18, C21.

# 1. Introduction

Rice is the main staple in Bangladeshi diet and 76.7% of the total cultivated area is devoted to rice production (BBS, 2012a). Although Bangladesh has made remarkable progress in rice production growth due to widespread adoption of the Green Revolution technology, the demand still outstrips supply and the country remains a net importer of rice (FPMU, 2008). For example, Bangladesh imported 380,000 mt of rice in 2013/14 (FPMU, 2014). Consequently, in the pursuit of meeting continuously rising demand for food, use of energy in agricultural sector has increased substantially in Bangladesh. For example, commercial energy intensity in agriculture has increased from only 1.78 in 2000 to a high level of 11.31 in 2008 and is projected to reach 24.00 in 2035 (Khosruzzaman, 2010). Use of inorganic fertilizer, a finite and non-renewable source of energy, is also on the rise. A total of 2.57 million mt of fertilizers (domestically produced and imported) was used in 2010 (BBS, 2012b). Rice production alone consumes about 80% of total fertilizers in Bangladesh (Balcombe et al., 2007). Despite such increase in the use of energy in agriculture, the growth of rice output remains a central concern since there is very limited potential to expand cultivation of the arable land. For example, the net sown area in Bangladesh has actually declined at an annual rate of 0.03% during the period 1986-2006 (Rahman, 2010a). Therefore, new technologies and/or strategies need to be applied in order to free the constraints of the closing land frontier in Bangladesh but at the same time continue to improve rice productivity. However, it is important to note that the choice of such technologies should be energy efficient as well because only then the system is likely to sustain in the long run and will exert less strain on the already energy deficient economy(Rahman and Rahman, 2013).

Nitrogen (N) plays a key role in rice production and is required in large amount. It is also the most limited nutrient in rice production and suffers from heavy system losses when applied as inorganic sources in puddle field (Hasanuzzaman et al., 2009; IFDC, 2013). Urea, which is a finite and non-renewable resource, is the most widely used source of N fertilizer globally including Bangladesh. A worldwide crisis of urea fertilizer in 2008, when its price increased from USD 277 per mt in August 2007 to USD 815 per mt in August 2008, spurred the need to economise on this widely used source of N fertilizer with urgency (IFDC, 2009).

The Fertilizer Deep Placement (FDP) strategy is developed by International Fertilizer Development Corporation (IFDC) after working with farmers for over 20 years, particularly in Bangladesh (IFDC, 2013). The principal aim of FDP strategy is to improve N use efficiency in transplanted rice production by reducing losses of applied N via ammonium volatilization and denitrification. This is because unutilized N is lost from the rice field and released to the environment where it is not needed. For example, about 70% of urea is lost to run off or the atmosphere (IFDC, 2013). FTF (2011) noted that the adoption of FDP strategy cuts N losses by 40%, thereby, reducing air and water pollution while increasing farmers' yield by more than 20% and also decreases negative environmental impacts of overuse of fertilizers. The FDP strategy consists of two key components. First key component is producing fertilizer 'briquette' by compacting commercially available urea fertilizer (e.g., which is known as Urea Super Granules or USG weighing roughly 1-3 grams per briquette). The second key component is placement of the urea briquettes (i.e., USG) below the soil surface. When used to fertilize irrigated rice, the briquettes are centred between four plants at a depth of 7-10 centimetres within seven days after transplanting. Placement can be done either by hand or with a mechanical applicator. The briquette releases N gradually, coinciding with the crop's requirements during the growing season (IFDC, 2013). Also, in this production process, N fertilizer is required to be applied only once for the entire crop season unlike conventional urea production process when 3-4 applications are required (mainly broadcasting first and then top-dressing subsequently at different stages of plant growth) (IFDC, 2013).

IFDC (2009) claimed that FDP strategy is spreading widely in Bangladesh which covered 500,000 ha of irrigated rice land and increased total rice production by 268,000 ton, labour use by 9.5 days per ha and net return by USD 188 per ha and also reduced fertilizer imports by 50,000 mt in 2009. IFDC (2013) further claimed that 2.5 million farmers are now using FDP strategy and it is being expanded to another 1 million farmers across the country and the strategy has saved the government of Bangladesh USD 29 million in purchases and subsidies on urea fertilizer. The Bangladesh Rice Research Institute (BRRI) also noted that the use of FDP strategy can minimize loss in N from soil and hence increase its effectiveness by 20-25% (BRRI, 2008). Hasanuzzaman et al. (2009) reported that the application of USG @ 75 kg/ha produced 22.03% more yield than normal urea application in modern Boro rice (dry winter season) cultivation in the experimental plots in Bangladesh. It is worth noting that FDP strategy requires additional use of energy for briquetting commercially available urea into USG.

Existing literature on the merit of FDP strategy is limited to general farm-management accounting focusing on economic profitability and/or field experiments focusing on savings in N fertilizer use and increase in rice yield (Hasanuzzaman et al., 2009; IFDC, 2013; BRRI, 2008). To our knowledge, there is no literature which has examined the performance of FDP strategy with respect to gains in production efficiency and productivity of rice when evaluated in terms of energy use. Our contribution to the existing literature of energy use in agriculture is that we have empirically examined the impact of the FDP strategy on energy productivity and technical energy efficiency in modern rice production at the farm-level in Bangladesh by applying a stochastic production frontier approach. The findings of the present study are expected to support academics, researchers, non-governmental organizations as well as policy makers with useful information to raise productivity of modern rice and contribute towards improving food security in Bangladesh while at the same time save the level of energy use in rice production.

The paper is organized as follows. Section 2 presents the methodology, analytical framework, study area and the data. Section 3 presents the results. Section 4 presents discussion and draws policy implications.

## 2. Methodology

### 2.1 Energy accounting approach

As a first step, standard energy input-output analysis (Rahman and Rahman, 2013; Mohammadi, et al., 2008; Canakci et al., 2005; Chauhan et al., 2006; Rahman and Barmon, 2012) was used to compare some basic performance measures of the FDP users and conventional urea users in modern rice cultivation for the two main growing seasons. These are: Boro (dry winter) and Aman (monsoon) seasons. The performance measures are defined as (Mohammadi, et al. 2008):

*Energy ratio (Energy use efficiency) = Energy output (MJ ha*$^{-1}$*) /Energy input (MJ ha*$^{-1}$*)* (1)

*Energy productivity = Yield (kg ha*$^{-1}$*)/Energy input (MJ ha*$^{-1}$*)* (2)

*Specific energy = Energy input (MJ ha*$^{-1}$*)/Yield (kg ha*$^{-1}$*)* (3)

*Net energy = Energy output (MJ ha*$^{-1}$*)–Energy Input (MJ ha*$^{-1}$*)* (4)

We applied standard energy coefficients from the existing published literature for conversion (Mohammadi et al., 2008; Canakci et al., 2005; Chauhan et al., 2006; Rahman and Barmon, 2012). Specifically, the production energy for briquetting machine (which is not available in the literature) was calculated as follows Canakci et al., (2005):

$$M_{pe} = (GM_p)/(TW) \qquad (5)$$

where $M_{pe}$ is energy of the briquetting machine to produce the amount of USG needed per unit (MJ per kg); G is the mass of briquetter, kg; $M_p$ is the production energy of the briquetter, (MJ per kg); T is the economic life, (hour); and W is the effective capacity, (kg per hour).

The diesel energy requirement was determined on the basis of fuel consumption (litre per hour). The data were converted into energy units and expressed in MJ per ha. Fuel consumption was computed as Mohammadi et al., (2008):

$$FC = P_m.R.SFC \tag{6}$$

where FC is the fuel consumption, (litre per hour); $P_m$ is the machine power, kW; R is the loading ratio, decimal; and SFC is the specific fuel consumption (0.25 litre kW per hour).

Table 1 presents the energy coefficients used in this study including literature sources.

### 2.2. Analytical framework: The stochastic production frontier model

Production inefficiency is usually analysed by its three components – technical, allocative, and scale inefficiency. In a production context, a farm is said to be technically inefficient, for a given set of inputs, if its output level lies below the frontier output (the maximum feasible output) (Rahman, 2003). The popular approach to measure efficiency, the technical efficiency component, is the use of frontier production function. We used the stochastic production frontier model developed by Aigner et al. (1977) to address our objectives to estimate energy productivity and technical energy efficiency of applying FDP strategy in modern rice production. The stochastic production frontier for the *i*th farmer is written as:

$$Y_i = f(X_i) - u_i + v_i \tag{7}$$

where $Y_i$ is the energy output, $X_i$ is the vector of energy inputs, $v_i$ is assumed to be independently and identically distributed $N(0,\sigma^2_v)$ two sided random error, independent of the $u_i$; and the $u_i$ is a non-negative random variable $(u_i \geq 0)$, associated with energy inefficiency in production which is assumed to be independently distributed as truncation at zero of the normal distribution with mean $-Z_i\delta$, and variance $\sigma_u^2$ ($|N(-Z_i\delta, \sigma^2_u|$), where $Z_i$ are the correlates of inefficiencies on farm *i*.

We used the single stage approach proposed by Battese and Coelli (1995) to determine the predictors of technical inefficiency which is related to a vector of farm-specific characteristics subject to statistical error, such that:

$$u_i = Z_i\delta + \zeta_i \geq 0 \qquad (8)$$

where, $Z_i$ are the farm-specific characteristics and the error $\zeta_i$ is distributed as $\zeta_i \sim N(0, \sigma_\zeta^2)$. Since $u_i \geq 0, \zeta_i \geq -Z_i\delta$, so that the distribution of $\zeta_i$ is truncated from below at the variable truncation point, $-Z_i\delta$.

The technical energy efficiency of farm *i* is defined as:

$$EFF_i = E[\exp(-u_i) \mid \xi_i] = E[\exp(-\delta_0 - \sum Z_i\delta \mid \xi_i) \qquad (9)$$

where *E* is the expectation operator. This is achieved by obtaining the expressions for the conditional expectation $u_i$ upon the observed value of $\xi_i$, where $\xi_i = v_i - u_i$. The stochastic production frontier and inefficiency effects functions are estimated jointly using Maximum Likelihood Estimation (MLE) procedure to obtain estimates of the unknown parameters. The likelihood function is expressed in term of the variance parameters, $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\gamma = \sigma_u^2 / \sigma^2$ Battese and Coelli (1995).

## 2.3. Data and variables

To assess the impacts of FDP strategy on modern Boro and Aman rice production, Shimlagachi village in Sharsha upazilla (sub-district) of Jessore district was selected. This village was purposively selected because sufficiently large number of farmers has adopted FDP strategy using USG while others are still using conventional urea in modern rice production. Initially, a detailed list of farmers who used FDP strategy and who used conventional urea in modern rice production was collected from the upazilla (sub-district) agricultural office. Then a total of 100 farmers using FDP strategy and another 100 farmers using conventional urea to produce modern rice in both Boro and Aman seasons were randomly selected. Selection of the FDP strategy users and conventional urea users from the same village will provide clear information on relative advantage of this strategy. This is because all farmers in a village face similar input and output prices, set of information regarding both technologies as well as the production environment, and therefore, any observed differences between the two groups of producers could be confidently attributed to FDP strategy alone. Detailed information on various inputs used and output of modern rice produced including socio-economic information of the farmers were collected through administering a structured and pre-tested questionnaire. The survey was conducted during May-June 2013 by one of the authors.

### 2.4. The empirical model

The general form of the Cobb-Douglas stochastic production frontier function is used. We did not use the translog model because we are using a large number of explanatory indicators. Moreover, Kopp and Smith (1980) suggest that the choice of functional form has a limited effect on technical efficiency. Consequently, the Cobb-Douglas specification is widely used in studies (e.g., Rahman and Rahman, 2013; Pishgarh-Komleh et al., 2011). The empirical model is written as:

$$\ln Y_i = \beta_0 + \sum_{j=1}^{11} \beta_j \ln X_{ij} + \sum_{m=1}^{4} \tau_m D_{im} + \alpha_{1i} FDP_i + v_i - u_i \qquad (10)$$

and

$$u_i = \delta_0 + \sum_{d=1}^{5} \delta_d Z_{id} + \zeta_i \tag{11}$$

where $Y_i$ is the rice energy output; $X_{ij}$ is $j$th energy input for the ith farmer; $D_{ij}$ are the dummy variables used to account for the zero values of input use and have the value of 1 if the $j$th energy input used is positive and zero otherwise specified as $ln\ \{max\ (X_j, 1 - D_j)\}$ following Battese and Coelli (1995); $FDP_i$ is the dummy variable to account for farmers using FDP strategy in their production process, $v_i$ is the two sided random error, $u_i$ is the one sided half-normal error, $ln$ natural logarithm, $Z_{id}$ variables representing socio-economic characteristics of the farm to explain inefficiency, $\zeta_i$ is the truncated random variable; $\beta_0$, $\beta_j$, $\tau_m$, $\alpha_l$, $\delta_0$, and $\delta_d$ are the parameters to be estimated.

A total of 11 production inputs (X) and three fertilizer user and one female labour user dummies (D) are used in the full specification, and five variables representing socio-economic characteristics of the farmer (Z) are included in the inefficiency effects model as predictors of technical energy inefficiency. Accounting for the impact of FDP strategy is implemented by estimating two versions of the empirical model. First, to examine its impact on rice energy productivity, the FDP dummy variable is included in the production frontier model (Model 1). Next, to examine its impact on technical energy efficiency, the FDP dummy variable is included in the inefficiency effects model (Model 2). Use of a total of 11 inputs implies that we have included all possible inputs required in the production process, thereby, reducing any potential missing variable bias. Among the inputs, we have used energy applied using male labour and female labour separately, as their energy coefficients are different and contribution of female labour in productivity and efficiency in the literature is rather mixed (Rahman and Barmon, 2012; Rahman 2010b). Variables included to predict technical efficiency are based on the existing literature and justification thereof (Rahman, 2010b; Rahman and Barmon, 2012; Rahman, 2003).

## 3. Results

### 3.1. Energy inputs and outputs of FDP and conventional urea applications

Table 2 presents energy inputs and outputs of modern rice production per ha for Boro and Aman seasons classified by the FDP and conventional urea users. Overall, energy inputs and outputs are much higher for Boro season as this is the most productive rice producing season that is highly dependent on supplementary irrigation unlike Aman season where the system is based on monsoon rain with occasional supplementary irrigation and hence use substantially low level of mechanical energy. The most noticeable difference between the FDP and conventional urea users is 50% reduction in energy from N fertilizer by the former group in both seasons, which establishes the fact that the FDP strategy significantly saves N fertilizer use ($p<0.01$). Also, use of male labour is higher for the FDP users which imply increase in employment opportunities provided that hired labour is used to meet the extra demand for labour. Otherwise it adds burden on family labour instead. Use of female labour is very low, but the conventional urea users use relatively more, almost twice as much. The principal reason may be the low level of wages paid to female labour. For example, the male wage rate is Taka 200 per day whereas the female labour wage rate is Taka 150 per day in the study area[1]. However, pesticide use is lower for the FDP users in both seasons which is encouraging as it not only saves energy input use but reduces potential pollution problem. The FDP users also use very high level of organic manure, particularly in the Boro season, whereas the conventional urea users do not apply it all in the Aman season, showing a strong contrast. The energy outputs were significantly higher for the

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[1] The exchange rate is USD 1 = Taka 83.60 in May 2013 (Bangladesh Bank, 2013).

FDP users in both seasons ($p<0.01$) consistent with the claims of IFDC (IFDC, 2013; IFDC, 2009).

Results from Table 3 clearly establish superior performance of the FDP users as compared with the conventional urea users in both seasons. The FDP users supersede with respect to all energy performance measures as compared with the conventional urea users for both seasons, thereby establishing energy input saving potential of this strategy while producing higher energy output at the same time. For example, total savings on energy inputs is 14.5% and 16.3% while net energy balance is 20.6% and 13.8% higher in Boro and Aman seasons, respectively for the FDP users as compared with the conventional urea users ($p<0.01$). The estimated yield and hence energy output of Boro modern rice is comparable to the estimates made by Nassiri and Singh (2009) but substantially higher than that worked out by Chauhan et al. (2006) reported for farms in India.

### 3.2. Productivity effects of FDP strategy

Parameter estimates of the stochastic production frontier along with inefficiency effect function (i.e., Model 1 and Model 2) are reported in Table 5 using the MLE procedure in STATA Version 10 software (StataCorp, 2008). First we tested for the validity of using the stochastic frontier framework, known as the frontier test. This is done by checking the sign of the third moment and the skewness of the Ordinary Least Squares (OLS) residuals of the data. The computed value of Coelli's (1995) standard normal skewness statistic (M3T) based on the third moment of the OLS residuals is 3.32 and tested against the null hypothesis of ($H_0$: M3T = 0) and is rejected at the 5% level of significance (Table 4). In other words, the null hypothesis of no inefficiency component is rejected and, therefore, use of the stochastic frontier framework is justified. The significant value of the coefficient on $\gamma$ reported in Table 5 also suggests presence of technical energy inefficiency.

Coefficients on the input variables have the expected positive sign (i.e., positive marginal products) except organic manure and seed energy inputs. The negative sign on the coefficient of these two variables implies overuse of these inputs which should be avoided. Since Cobb-Douglas model is used, the coefficients can be directly interpreted as elasticities. Four types of inorganic fertilizers significantly influence energy productivity of rice. The combined elasticity of the all inorganic fertilizers is estimated at 0.33 and 0.38 in Models 1 and 2, implying that a one percent increase in total inorganic fertilizer use will raise energy productivity in rice by 0.33% to 0.38% which is substantial. This finding establishes that fertilization using inorganic sources is the key to improve productivity of rice in Bangladesh which is perhaps responsible for increasing energy intensity in agriculture. The influence of mechanical power energy is also important in raising productivity of rice with an elasticity value of 0.10. Accounting for zero use of some inputs proved to be effective as the null hypothesis ($H_0$: $\iota_1 = \iota_2 = \ldots = \iota_4 = 0$) is strongly rejected at the 1% level of significance (Table 4). Model 1 in Table 5 clearly shows that the adoption of FDP strategy significantly increases energy productivity of rice ($p<0.01$) which econometrically confirms its productivity advantage presented in Section 3.1 and Table 3.

### 3.3. Efficiency effects of FDP strategy

The distribution of technical energy efficiency scores is presented in Table 6. It is clear from Table 6 that the technical energy efficiency levels of the modern rice farmers are quite high and the mean energy efficiency level is estimated at 82%. The implication is that the energy output of modern rice can still be increased by 18% by eliminating inefficiencies in production. When classified by FDP adoption status, Table 5 clearly shows that the FDP users are actually producing at a significantly higher level of technical energy efficiency estimated at 88% which is 12 points higher than the conventional urea users estimated at 76% ($p<0.01$). Although the mean technical energy efficiency of the conventional urea users is quite similar to those reported for paddy production in India (Chauhan, 2006; Nassiri and Singh, 2009), the efficiency levels of FDP users are significantly higher, thereby clearly establishing that FDP strategy improves technical energy efficiency as well.

The predictors of technical energy inefficiency are presented at the lower panel of Table 5 (Model 2). The joint test of hypothesis of no inefficiency effects ($H_0$: $\delta_1 = \delta_2 = \ldots. = \alpha_1 = 0$) was strongly rejected at 1% level of significance (Table 4). Farmers who have other income sources are relatively inefficient. This is consistent with the findings of Rahman (2003) who reported that farmers with higher opportunity to engage in off-farm work fail to pay attention to their crops relative to other farmers. The results also show that higher ratio of female labour increases inefficiency (Model 1). This is in contrast with Rahman (2010b) who reported that female labour improves technical efficiency. The reason may be that the female labourers do not have the type of skills required for FDP strategy. Result from Model 2, however, shows no effect of female labour on inefficiency, consistent with Rahman and Barmon (2012). Tenants are relatively efficient than owner operators (Model 2) which is consistent with the findings of Rahman (2010b). Model 2 of Table 5 clearly shows that the FDP users are relatively technically efficient as compared with conventional urea users, which econometrically confirms the results reported in Table 6.

## 4. Discussion and policy implications

The principle aim of this study was to econometrically investigate the impacts of FDP strategy on energy productivity and technical energy efficiency in modern rice production under farm-level conditions, as it holds the promise to economise on a vital, finite and expensive resource (urea fertilizer) while at the same time increase rice productivity. IFDC (2013) claimed that the increased value of rice produced by applying FDP strategy in Bangladesh was USD 177.22 million in 2012. Given low growth in modern rice productivity over time, estimated at 1.4% per annum during 1986-2006 (Rahman, 2010), farmers are forced to seek improved way of production that could economise on resources while increase productivity. Although adoption of any new strategy is a risky business and takes time, it seems that Bangladeshi farmers are willing to undertake measured risks, as 2.5 million farmers have already adopted this strategy in a space of few years (IFDC, 2013). Technological change includes two components: product innovation and process innovation. The FDP strategy represents a process innovation with some modification of the already used product, urea (i.e., converting commercially available urea fertilizer into USG through briquetting). Also, the process required to apply USG is not strictly new because Bangladeshi farmers has been manually transplanting individual seedlings in irrigated rice fields during Aman and Boro seasons for years. The FDP strategy only requires placing USG in the middle of four plants using almost similar technique as used for transplanting rice seedlings. Therefore, adoption of FDP strategy is not likely to be very challenging as it makes use of a practice that the farmers are already familiar with.

Our results clearly establish that the adoption of FDP strategy significantly improves energy productivity and technical energy efficiency. The net gain in saving on energy inputs and increasing energy outputs is substantial. Furthermore, the FDP users not only reduced the use of N fertilizer but also pesticides which is very encouraging. The relative gains are much higher for the Boro season as compared with the Aman season. The FDP users are not only producing more energy output per unit of land area but are also operating at a very high level of technical energy efficiency, implying that the farmers have learned to apply this strategy correctly in a short space of time which is an important feature to consider in developing new technologies.

The policy implication is clear. The FDP strategy should be promoted throughout Bangladesh so that the farmers could economise on scarce inputs while increase outputs of rice and contribute towards improving food security of the nation following an energy efficient path. The plan of the Feed the Future (FTF) Multi-year Strategy (2011–2015) to promote FDP strategy to 3.5 million farmers in 120 sub-districts of 16 districts in southern Bangladesh is a step in the right direction (FTF, 2011). However, effective dissemination of this strategy will require measures to support establishment of small-scale briquetting enterprises. For example, IFDC's trial of FDP strategy in India did not take off because briquetting facilities to produce USG were not in place (IFDC, 2009). According to IFDC (2013), FDP briquettes are currently produced by little more than 1,000 entrepreneurs with small scale briquetting machines in Bangladesh, which is clearly inadequate if nationwide expansion of this strategy is to be implemented effectively in a short space of time. Therefore, measures with appropriate incentive mechanisms are required to increase the number of entrepreneurs to become involved in supporting FDP strategy dissemination (through rapid conversion of conventional urea into USG) which holds the promise to improve food security of the economy while exerting less pressure on energy use in agriculture.

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Table 1. Energy coefficients used for rice cultivation

| Variables | Unit | Energy equivalents (MJ per unit) | References |
|---|---|---|---|
| **Inputs** | | | |
| Paddy seed | kg | 14.70 | Chauhan et al. (2006) |
| Male labour | hr | 1.96 | Chauhan et al. (2006) |
| Female labour | hr | 1.57 | Chauhan et al. (2006) |
| Farm yard manure | kg | 0.30 | Chauhan et al. (2006) |
| Power tiller | kg | 62.20 | Rahman and Barmon (2012) |
| Diesel | litre | 56.31 | Chauhan et al. (2006) |
| Briquetting machine | kg | 20.82 | Calculated |
| Pesticides | kg/litre | 120.00 | Chauhan et al. (2006) |
| Nitrogen (N) | kg | 66.14 | Mohammadi et al. (2008) |
| Phosphorus ($P_2O_5$) | kg | 12.44 | Mohammadi et al. (2008) |
| Potassium ($K_2O$) | kg | 11.15 | Mohammadi et al. (2008) |
| Sulphur (S) | kg | 1.12 | Mohammadi et al. (2008) |
| Zinc (Zn) | kg | 20.90 | Chauhan et al. (2006) |
| **Outputs** | | | |
| Paddy | kg | 14.70 | Chauhan et al. (2006) |
| Straw | kg | 2.25 | Rahman and Barmon (2012) |

Table 2. Energy use per hectare in modern rice production of FDP users and conventional urea users

| | **Boro season** | | **Aman season** | |
|---|---:|---:|---:|---:|
| | **FDP with USG** | **Conventional urea** | **FDP with USG** | **Conventional urea** |
| **Inputs** | | | | |
| Male labour energy | 2792.07 | 2399.91 | 2749.80 | 2351.77 |
| Female labour energy | 35.62 | 67.48 | 32.68 | 72.89 |
| Seed energy | 538.81 | 535.51 | 542.67 | 545.97 |
| Mechanical power energy | 11163.56 | 10975.28 | 4430.24 | 3818.41 |
| Organic manure energy | 1407.93 | 682.00 | 391.39 | 0.00 |
| N – fertilizer energy | 4984.68 | 9700.54 | 3806.86 | 7502.09 |
| P – fertilizer energy | 839.70 | 845.07 | 617.93 | 675.16 |
| K – fertilizer energy | 698.83 | 629.94 | 519.74 | 507.21 |
| S – fertilizer energy | 22.75 | 21.92 | 15.87 | 14.78 |
| Zn – fertilizer energy | 75.86 | 79.42 | 41.08 | 42.45 |
| Pesticide energy | 1450.73 | 2145.32 | 1344.25 | 1784.12 |
| **Outputs** | | | | |
| Paddy energy | 98779.92 | 89820.57 | 72521.03 | 68025.87 |
| Straw energy | 2231.72 | 2104.31 | 2026.69 | 2049.47 |

Source: Field Survey, 2013.

Table 3. Energy accounts of modern rice production by FDP users and conventional urea users

| Measurements | Units | Boro season | | | Aman season | | |
|---|---|---|---|---|---|---|---|
| | | **FDP with USG** | **Conventional urea** | **Mean difference (USG vs Urea)** | **FDP with USG** | **Conventional urea** | **Mean difference (USG vs Urea)** |
| Energy inputs | MJ per ha | 24010.56 | 28082.41 | –4071.85*** | 14492.50 | 17314.83 | –2822.32*** |
| Energy outputs | MJ per ha | 101011.60 | 91924.88 | 9086.76*** | 74547.71 | 70075.34 | 4472.38*** |
| Paddy yield | kg per ha | 6719.72 | 6110.24 | 609.48*** | 4933.40 | 4627.61 | 305.79*** |
| Specific energy | MJ per kg | 3.58 | 4.63 | –1.04*** | 2.97 | 3.77 | –0.79*** |
| Energy use efficiency | -- | 4.24 | 3.33 | 0.91*** | 5.32 | 4.10 | 1.21*** |
| Energy productivity | kg per MJ | 0.28 | 0.22 | 0.06*** | 0.35 | 0.27 | 0.08*** |
| Net energy | MJ per ha | 77001.08 | 63842.47 | 13158.61*** | 60055.21 | 52760.51 | 7294.70*** |

Note: *** significant at 1 % level (p<0.01)

Table 4. Hypothesis tests

| **Hypotheses** | **Critical value of $\chi^2$(v, 0.95)** | **Likelihood Ratio statistic** | **Decision** |
|---|---|---|---|
| Frontier test<br>($H_0$: M3T = 0, i.e., no inefficiency component) | 1.96<br>(z-statistic) | 3.32**<br>(z-statistic) | Reject $H_0$<br>Frontier not OLS |
| No effect of users of fertilizers, organic manures, and female labour on productivity<br>($H_0$: $\iota_1 = \iota_2 = \ldots. = \iota_4 = 0$) | 9.49 | 28.16*** | Reject $H_0$<br>Significant effect on productivity |
| No effect of socio-economic characteristics on inefficiency<br>($H_0$: $\delta_1 = \delta_2 = \ldots. = \alpha_1 = 0$) | 12.59 | 49.64*** | Reject $H_0$<br>Inefficiencies are jointly explained by these variables |

Note: *** significant at 1 % level ($p<0.01$)
** significant at 5 % level ($p<0.05$)

Table 5: Joint parameter estimates of the stochastic production frontier with inefficiency effects model

| **Variables** | **Parameter** | **Model 1** | | **Model 2** | |
|---|---|---|---|---|---|
| | | **Coefficient** | **t-ratio** | **Coefficient** | **t-ratio** |
| **Stochastic production frontier model** | | | | | |
| Constant | $\beta_0$ | 10.4044*** | 21.45 | 10.4267*** | 20.36 |
| Male labour energy | $\beta_1$ | -0.0119 | -0.45 | -0.0324 | -1.20 |
| Female labour energy | $\beta_2$ | 0.0185* | 1.70 | 0.0109 | 0.98 |
| Seed energy | $\beta_3$ | -0.2766*** | -5.40 | -0.2589*** | -4.77 |
| Mechanical power energy | $\beta_4$ | 0.0997*** | 6.90 | 0.1012*** | 6.68 |
| Organic manure energy | $\beta_5$ | -0.0221** | -2.12 | -0.0224** | -2.11 |
| N – fertilizer energy | $\beta_6$ | 0.0808*** | 3.13 | 0.0946*** | 3.60 |
| P – fertilizer energy | $\beta_7$ | 0.0764*** | 2.50 | 0.1028*** | 3.29 |
| K – fertilizer energy | $\beta_8$ | 0.0759*** | 2.85 | 0.0695*** | 2.49 |
| S – fertilizer energy | $\beta_9$ | -0.0015 | -0.07 | -0.0070 | -0.32 |
| Zn – fertilizer energy | $\beta_{10}$ | 0.0971*** | 3.79 | 0.1163*** | 4.44 |
| Pesticide energy | $\beta_{11}$ | 0.0124* | 1.78 | 0.0120 | 1.59 |
| Organic manure users | $\tau_1$ | 0.2172*** | 3.03 | 0.2025*** | 2.76 |
| Gypsum fertilizer users | $\tau_2$ | 0.0205 | 0.32 | 0.0324 | 0.49 |
| Zinc fertilizer users | $\tau_3$ | -0.3755*** | -3.50 | -0.4528*** | -4.13 |
| Female labour dummy | $\tau_4$ | -0.0802* | -1.67 | -0.0480 | -1.00 |
| FDP strategy users | $\alpha_1$ | 0.1509*** | 6.60 | -- | -- |
| **Variance Parameters** | | | | | |
| $\sigma^2 = \sigma_u^2 + \sigma_v^2$ | $\sigma^2$ | 0.0469*** | 4.36 | 0.0083*** | 14.14 |
| $\gamma = \sigma_u^2/(\sigma_u^2 + \sigma_v^2)$ | $\gamma$ | 0.8657*** | 23.89 | 0.7977*** | 18.77 |
| Log likelihood | | | | | |
| Wald $\chi^2$ (16 df and 15 df) | $\chi^2$ | 392.38*** | | 389.74*** | |
| **Inefficiency effects function** | | | | | |
| Constant | $\delta_0$ | -1.3476* | -1.83 | 0.2456 | 1.35 |
| Age of the farmer | $\delta_1$ | 0.0026 | 0.28 | 0.0007 | 1.27 |
| Education of the farmer | $\delta_2$ | -0.0108 | -0.53 | -0.0015 | -1.21 |
| Share of other income | $\delta_3$ | -0.0010 | -0.23 | 0.0000 | -0.28 |
| Tenurial status | $\delta_4$ | -0.5882 | -1.25 | -0.0194* | -1.81 |
| Female labour ratio | $\delta_5$ | 1.3819* | 1.71 | 0.0354 | 0.85 |
| FDP strategy users | $\alpha_1$ | -- | -- | -0.1545*** | -6.44 |
| Total number of observations | | 400 | | 400 | |

Note: *** significant at 1 % level ($p<0.01$)
** significant at 5 % level ($p<0.05$)
* significant at 10 % level ($p<0.10$)

Table 6: Technical energy efficiency distribution

| **Items** | **Percentage of farmers (Model 2)** |
|---|---|
| **Efficiency levels** | |
| up to 80% | 50.00 |
| 81 – 90% | 44.00 |
| 91% and above | 6.00 |
| **Mean efficiency by FDP strategy** | |
| FDP users | 0.88 |
| Conventional urea users | 0.76 |
| Mean efficiency difference (FDP vs conventional urea users) | 0.12 |
| t-statistic of mean efficiency difference (FDP vs conventional urea users) | 89.02*** |
| **Overall** | |
| Mean efficiency score | 0.82 |
| Standard deviation | 0.07 |
| Minimum | 0.73 |
| Maximum | 0.98 |