1 INTRODUCTION

Energy security is an essential condition for food security and rural poverty reduction in low-income countries (Barnes & Floor, 1996; HLPE, 2013; Lahimer et al., 2013). Rural development is often hampered by limited access to the global energy system dominated by fossil fuels and centralized electricity production, especially in landlocked areas (Demirbas & Demirbas, 2007; HLPE, 2013; Kaygusuz, 2011). Many rural communities still largely depend on solid fuels, such as coal, wood, dung and crop residues, which demand substantial time investments and entail severe health threats (Bruce, Perez-Padilla, & Albalak, 2000; WHO, 2016). A search for available, affordable and sustainable alternative energy sources has recently been initiated (Chester, 2010; Lahimer et al., 2013; Lewis & Pattanayak, 2012). In this respect, developing countries might benefit substantially from locally produced liquid biofuels (Demirbas, 2009; Demirbas & Demirbas, 2007;
Kaygusuz, 2011; Kline et al., 2017). In particular, much hope is set on biofuels derived from nonedible feedstock grown on marginal or underutilized lands, since this approach could reduce trade-offs with food systems (Ewing & Msangi, 2009; Fritsche et al., 2017; Sorda, Banse, & Kernfert, 2010). Apart from increased energy self-reliance, these alternative biofuels could lead to income and employment generation (HLPE, 2013), as well as to climate change mitigation (Hill, Nelson, Tilman, Polasky, & Tiffany, 2006; Tilman et al., 2009).

Substantial investments have been made world-wide in using jatropha (Jatropha curcas), an oilseed shrub, as an alternative biofuel feedstock. However, the financial viability of jatropha-based biodiesel systems is often low and highly uncertain, especially in monoculture set-ups (Achten, Sharma, Muys, Mathijs, & Vantomme, 2014; van Eijck et al., 2017). In their global review, van Eijck et al. (2014) found that financial performance is highly variable and that only 27% of studies report substantial returns across the value chain. The principal reasons are limited yields, along with fickle fossil fuel prices, low by-product valorization and high labour requirements (Borman, Von Maltitz, Tiwari, & Scholes, 2013; van Eijck et al., 2014; Soto, 2017). Moreover, several methodological shortcomings lead to large uncertainties on profitability: many studies (a) lack a formalized cost-benefit analysis, (b) use only secondary data, (c) do not figure in parameter uncertainties, (d) do not include full opportunity costs of land and labour, and/or (e) only focus on farmers while externalizing other value chain actors (see also van Eijck et al., 2014).

Low financial feasibility of jatropha monocultures has shifted attention towards biofuel production from native oilseed trees in small-scale agroforestry set-ups (Achten, Akinnifesi et al., 2010; Fritsche et al., 2017; von Maltitz, Gasparatos, & Fabricius, 2014). These agroforestry-based systems involve planting of oilseed trees on field edges, in homegardens, and on fallow and communal land, thereby aiming at decreasing opportunity costs, increasing overall farm productivity and improving ecosystem services provisioning (Jose, 2009; Malézieux et al., 2009; Sharma et al., 2016). Moreover, native trees usually have traditional value chains, which improves by-product valorization, local farmers are often familiar with their agronomy, and they can be considered noninvasive (Edrisi et al., 2015; Gowda, Prasanna, Vijaya Kumar, Haleshi, & Rajesh Kumar, 2014). Nevertheless, as for jatropha monocultures, the lack of methodologically sound studies obscures the actual potential of agroforestry-based biofuel systems as local sources of energy, income, employment and ecosystem services.

This study creates a framework for evaluating the profitability of agroforestry-based biofuel value chains, by addressing common methodological shortcomings in the literature on novel biofuels. It develops a cost-benefit analysis that explicitly quantifies variability and uncertainty in economic performance across different value chain options and actors. It avoids common pitfalls by considering farmer-specific opportunity costs, and by using on-field yield measurements and other primary data. The developed general framework can be used to determine whether, in which configurations, for whom and to which extent agroforestry-based biofuel value chains are profitable, and how this depends on a range of key factors.

The applicability of the framework is illustrated by implementing it to explore the long-term financial performance of pongamia value chains in South India. Pongamia (Millettia pinnata) is a leguminous, drought-resistant oilseed tree native to the Indian subcontinent and Southeast Asia but now distributed pannotropically (CABI, 2018; GBIF Secretariat, 2017; Meena Devi, Vijayalakshmi, & Nagendra Prasad, 2008; Murphy et al., 2012). It is particularly cultivated throughout India (Altenburg et al., 2009; Kesari & Rangan, 2010; Korwar et al., 2014). Its nonedible seed oil can be processed to biodiesel for use in engines (Karmee & Chadha, 2005; Naik, Meher, Naik, & Das, 2008; Raheman & Phadate, 2004), while the oil is traditionally used as a lamp fuel, and for medicinal and industrial applications (Meena Devi et al., 2008; Sangwan, Rao, & Sharma, 2010). The seed cake by-product is commonly used as a fertilizer, and other tree parts have fuel, fertilizer, pesticidal and medicinal uses (Al Muqarrabun, Ahmat, Ruzaaina, Ismail, & Sahidin, 2013; CABI, 2018; Dalemans, Muys, & Maertens, 2019; Sangwan et al., 2010). Pongamia tree cultivation entails various ecosystem services, such as shading, hedging, ornamenting and soil conservation (Dalemans et al., 2019; Meena Devi et al., 2008). Furthermore, several life cycle assessment studies indicate that biodiesel production from pongamia plantations may lead to greenhouse gas emission reductions relative to fossil fuels, although potential emissions from land use change were not accounted for (Cox, Renouf, Dargan, Turner, & Klein-Marcuschamer, 2014; Farine et al., 2012; Pragya, Sharma, & Gowda, 2017). Despite the benefits, few studies have investigated the economic viability of pongamia cultivation (Abadi et al., 2016; Bohra, Sharma, Saxena, Sabhlok, & Ramakrishna, 2016; Gunatilake, 2011; Murphy et al., 2012), and financial outcomes remain unclear.

2 | MATERIALS AND METHODS

2.1 | Profitability evaluation framework

2.1.1 | Functional and temporal units

Functional and temporal units should be explicitly specified in agroforestry set-ups. First, profitability should ideally be assessed for the entire land use system. However, there is often still limited understanding on competition and facilitation features of novel biofuel trees, and on their ecosystem (dis)services. Therefore, the proposed quantitative analysis

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**Table 2.1**

| MATERIALS AND METHODS |
|-----------------------|
| Profitability evaluation framework |
| Functional and temporal units |

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2.1.1 Functional and temporal units

Functional and temporal units should be explicitly specified in agroforestry set-ups. First, profitability should ideally be assessed for the entire land use system. However, there is often still limited understanding on competition and facilitation features of novel biofuel trees, and on their ecosystem (dis)services. Therefore, the proposed quantitative analysis
will consider an oilseed tree monoculture, while the extrapolation to an agroforestry-based system will be qualitatively assessed. The functional unit for calculating the profitability measures will be a monoculture of size $A$, for all value chain actors. Second, since oilseed trees are perennials whose yield only starts after several years and strongly varies afterwards, profitability should be calculated for an extensive period ($= k$ years), from planting up to several years after yield stabilization.

### 2.1.2 Profitability measures

The evaluation framework considers two fundamental value chain actors: farmers and processors. In each year $i$ and for each value chain $j$, oilseed tree cultivation and processing entails various revenues ($R_{ij}$) and costs ($C_{ij}$) for these actors. Labour and land inputs are substantial in many operational activities, and the corresponding costs are considered separately due to their inherent complexity. This is because both production factors can either be hired (land can also be bought, which is treated as a hiring cost in the first year), or be provided by the actor itself. Hired labour and land costs are easily monetized by using market wages ($W_{ij}$) and rental prices ($H_{ij}$), respectively. These costs are relatively uniform across individuals, and can therefore be directly added to the cost-benefit analysis without loss of generality. Self-provided labour and land (hereafter referred to as family labour and land), however, involves reallocation of these production factors from other activities; therefore, they should be valued in terms of opportunity costs. Opportunity costs are highly individual-specific, implying that they cannot be directly added to the cost-benefit analysis without making this analysis individual-specific. Rather, they serve as reference figures with which outcomes should be compared.

To make this more specific, four scenarios are distinguished by allowing for each production factor that it is either entirely hired or entirely family-provided:

#### 1. Hired land and labour

In this scenario, both land and labour costs are monetized and valued in the cost-benefit analysis at market rental and wage rates, respectively. The profit of biofuel tree cultivation/processing in year $i$ and for value chain $j$ ($P_{ij}$) is then calculated as:

$$P_{ij} = R_{ij} - C_{ij} - A \times H_{ij} - L_{ij} \times W_{ij}$$

where $L_{ij}$ is the time required for all relevant operations.

#### 2. Hired land, family labour

In this scenario, only land costs are monetized and valued in the cost-benefit analysis at market rental rates. Profitability is assessed by comparing the return to labour of biofuel tree cultivation/processing in year $i$ and for value chain $j$ ($RL_{hf,ij}$), calculated as:

$$RL_{hf,ij} = \frac{R_{ij} - C_{ij} - A \times H_{ij}}{L_{ij}}$$

with the returns to labour of other potential activities, which represent the opportunity cost of family labour.

#### 3. Family land, hired labour

In this scenario, only labour costs are monetized and valued in the cost-benefit analysis at market wage rates. Profitability is assessed by comparing the return to land of biofuel tree cultivation/processing in year $i$ and for value chain $j$ ($RA_{hf,ij}$), calculated as:

$$RA_{hf,ij} = \frac{R_{ij} - C_{ij} - L_{ij} \times W_{ij}}{A}$$

with the returns to land of other potential activities, which represent the opportunity cost of family land.

#### 4. Family land and labour

In this scenario, the returns to labour and land of biofuel tree cultivation/processing in year $i$ and for value chain $j$ (respectively $RL_{ff,ij}$ and $RA_{ff,ij}$), are calculated as:

$$RL_{ff,ij} = \frac{R_{ij} - C_{ij}}{L_{ij}}$$

$$RA_{ff,ij} = \frac{R_{ij} - C_{ij}}{A}$$

Profitability is only guaranteed if the returns to labour and land for biofuel tree cultivation/processing are both higher than the returns to labour and land, respectively, of other potential activities.

The returns of other activities, i.e., the opportunity costs, can be calculated for individual farmers and compared with returns of biofuel tree cultivation. The return to labour of biofuel tree cultivation can be compared with the return to labour of current on-farm and off-farm activities. The return to land of biofuel tree cultivation can be compared with the return to land of current farm activities. In case of processors, returns can be compared with the returns of feasible alternative investments, though these might be hard to identify.

Each of the five profitability measures is calculated for every year $i$. In order to facilitate an overall comparison of the different value chains, a single net present value (NPV) is calculated for each measure by discounting and summing up its values over the entire $k$-year period. A discount rate of $n$
% is applied. The respective net present profit and returns are calculated in Equations (6)–(10):

\[ P_j = \sum_{i=1}^{k} \frac{P_{ij}}{(1+i)^n} \]  
\[ RL_{lf,j} = \sum_{i=1}^{k} \frac{RL_{lf,j}}{(1+i)^n} \]  
\[ RA_{ph,j} = \sum_{i=1}^{k} \frac{RA_{ph,j}}{(1+i)^n} \]  
\[ RL_{ff,j} = \sum_{i=1}^{k} \frac{RL_{ff,j}}{(1+i)^n} \]  
\[ RA_{ff,j} = \sum_{i=1}^{k} \frac{RA_{ff,j}}{(1+i)^n} \]

2.1.3 | Input parameters

Revenues, costs, and labour and land figures in Equations (1)–(5), are calculated from a set of case-specific parameters. A distinction is made between stochastic input parameters and nonstochastic (or fixed) input parameters. The former are inherently spatially and temporally variable, and/or entail a certain degree of uncertainty on their values. In order to represent this variability and uncertainty, probability distributions rather than fixed values are used for these input parameters.

2.1.4 | Profitability calculation and visualization

To account for forward propagation of input parameter variability and uncertainty towards the model’s output, distributions of the profitability measures listed in Section 2.1.2, rather than fixed values, are calculated using Monte Carlo simulations. First, in order to assess variability and uncertainty in the outcomes, the estimated kernel probability density functions of the net present values (Equations 6–10) are visualized. Value chain performances are compared by contrasting net present values within the same Monte Carlo runs. Comparing within the same runs eliminates variation from stochastic variables that are shared between value chain scenarios, allowing for a clearer separation in value chain performance. Second, in order to visualize an easily interpretable “average outcome/trend” over the simulation period, the median values of the five profitability measures (Equations 1–5) in each of the k years after planting are plotted.

2.1.5 | Sensitivity analysis

In order to assess how variability and uncertainty in the outcomes are apportioned to the different stochastic input parameters, a sensitivity analysis is implemented by calculating correlations between the net present values (Equations 6–10) and the stochastic input parameters. High absolute correlation indicates that the input parameter has a large share in forward propagation of variability and uncertainty, or in other words that it strongly drives profitability variation. The opposite is true for low absolute correlation.

2.1.6 | Optimization scenarios

The sensitivity analysis indicates which stochastic model inputs have no or only marginal effects on profitability variation. To simplify the model, these parameters are fixed at their mean level. On the other hand, the sensitivity analysis identifies crucial determinants for profitability. These are the parameters that should be focused upon to identify which value chain innovations are required to increase profitability for all value chain actors. Innovations could include for instance improving oilseed yield, optimizing labour productivity and mechanical efficiency, or modifying infrastructure and price structures. In accordance with the sensitivity analysis results, innovations are assessed for their potential to improve profitability, and the extent to which parameter changes are required is evaluated.

2.2 | Application to pongamia value chains in South India

2.2.1 | Pongamia value chains in Hassan district, India

Since 2007, biofuel value chains based on small-scale agroforestry systems are being developed in Hassan district, Karnataka state, India – a geophysically diverse district of 6,814 km² – by a university – government partnership (Gowda et al., 2014; Lokesh, Mahesh, Gowda, & White, 2015). This so-called Biofuel Program (BP) stimulates farmers to plant oilseed trees on field edges, in homegardens and on fallow land, by information dissemination and free tree seeding distribution. Novel biofuel species are used, including pongamia (Millettia pinnata), neem (Azadirachta indica), mahua (Madhuca indica) and simaroub (Simarouba glauca). This study focuses on pongamia, which has the highest adoption potential in Hassan district according to previous studies (Dalemans et al., 2018, 2019). Apart from feedstock production, the BP also supports feedstock processing at different scales. On the one hand, it distributes small-scale oil-expelling equipment to villages free of charge, which enables on-site extraction and use of seed oil and cake by the communities themselves. On the other hand, it buys tree fruits and seeds from farmers, which it subsequently processes to seed oil, cake and biodiesel in the extension centre (= Biofuel Park). Processing to seed oil
This study distinguishes different pongamia-based value chains according to the end products and processing scheme, as described in Table 1. As pongamia seeds are protected by a hard shell, fruits need to be deshelled first. Deshelling can either be done manually by farmers using stones or rods, or mechanically in the Biofuel Park using specialized equipment. Next, oil is expelled mechanically from the seeds, for which various equipment sizes are available: in villages (home scale), in the Biofuel Park (demonstration scale) and in private enterprises (industrial scale). Finally, the oil can be converted to biodiesel using specialized equipment. Currently, conversion is only done in the Biofuel Park, yet conversion by industrial processors is also considered as a hypothetical scenario. Seven value chain scenarios are considered (Table 1), for which profitability is quantified for the different actors in the chain.

### 2.2.2 | Functional and temporal unit specifications

The functional unit used for the case study is a pongamia monoculture of one hectare (ha). A calculation period of 30 years after planting is used, as pongamia starts bearing oilseeds after 5 years, and maximal yield (in ton/ha) is assumed to be achieved at 25 years.

### 2.2.3 | Profitability measures

Revenues and costs are constituted as follows. Farmers and processors sell one to three end products (Table 1), with revenues depending on the end products’ yield and market value. Farmers can incur costs from field preparation, seedling procurement, planting, tree management, fruit collection, fruit deshelling, product transport and oil expelling. The latter three can also apply to processors, along with biodiesel conversion costs. Additionally, processors have to procure feedstock (fruits or seeds), the cost of which depends on the feedstock’s yield and market value.

Two simplifications are used to calculate the profitability measures (Equations 1–5). First, it should be noted that farmland rentals and transactions are rare in the region; farm production is usually done on inherited family land. Correspondingly, only self-provision of land applies to farmers, and Equations (1) and (2) will not be considered for them. Opportunity costs of labour and land are calculated by considering all current on- and off-farm activities. Second, processors in the area usually hire labour for all required operations. In addition, abstraction is made from initial investment costs – such as land acquisition and infrastructural development – and overhead. Therefore, only Equation (1) is considered for processors – with zero land costs.
| Group                      | Individual parameters                        | Unita | Normal distribution | Data source                  |
|----------------------------|---------------------------------------------|-------|---------------------|------------------------------|
|                            |                                             |       | Mean | SD    | Bounds (in SD) |                             |
| Yield & collection         | Fruit yield at 25 years – Low yield scenario | ton/ha | 6.00 | 3.00  | 1.0           | Yield project               |
|                            | Seed yield at 25 years – High yield scenario | ton/ha | 9.16 | 0.86  | 1.0           | BP information              |
|                            | Seed/fruit mass ratio                       | –     | 0.55 | 0.14  | 1.5           | Yield project; BP information |
|                            | Oil content                                 | %     | 34.69 | 2.85  | –             | Yield project               |
|                            | Collection rate, low yield scenario         | kg fruits/(hr*person) | 7.01 | 3.55  | 1.0           | Yield project; Farmer survey |
|                            | Collection rate, high yield multiplication factor | –     | 1.50 | 0.20  | 1.0           | Expert interview            |
| Processing                 | Deshelling rate - Manual                    | kg fruits/(hr*person) | 3.60 | 0.75  | 1.0           | Yield project; Farmer survey |
|                            | Deshelling rate - Mechanical                | kg fruits/(hr*person) | 50.00 | 16.67 | 1.0           | BP information              |
|                            | Deshelling loss - Manual                    | %     | 5.00 | 1.67  | 1.0           | BP information              |
|                            | Deshelling loss - Mechanical                | %     | 20.00 | 6.67  | 1.0           | BP information              |
|                            | Expelling rate - Village                    | kg seeds/(hr*person) | 12.00 | 4.00  | 1.0           | BP information              |
|                            | Expelling rate - Biofuel Park               | kg seeds/(hr*person) | 30.00 | 10.00 | 1.0           | BP information              |
|                            | Expelling rate - Industrial scale           | kg seeds/(hr*person) | 400.00 | 50.00 | 1.0           | BP information              |
|                            | Expelling efficiencyb - Village             | %     | 66.00 | 8.25  | 1.0           | BP information              |
|                            | Expelling efficiencyb - Biofuel Park/Industrial scale | %     | 71.00 | 8.88  | 1.0           | BP information              |
|                            | Conversion rate - Biofuel Park              | litre oil/hr | 12.50 | 4.17  | 1.0           | BP information              |
|                            | Conversion rate - Industrial scale          | litre oil/hr | 750.00 | 250.00 | 1.0           | BP information              |
|                            | Conversion cost - Biofuel Park              | INR/litre oil | 20.00 | 2.50  | 1.0           | BP information; Lokesh et al. (2015) |
|                            | Conversion cost - Industrial scale          | INR/litre oil | 10.50 | 1.31  | 1.0           | BP information              |
| Prices & wages             | Fruit price                                 | INR/kg | 7.00 | 2.00  | 1.0           | BP information              |
|                            | Seed price                                  | INR/kg | 21.30 | 6.59  | 1.5           | Farmer survey               |
|                            | Oil price                                   | INR/L  | 70.00 | 10.00 | 1.0           | BP information              |
|                            | Seed cake price                             | INR/kg | 21.00 | 5.00  | 1.0           | BP information              |
|                            | Biodiesel price                             | INR/L  | 53.00 | 10.00 | 1.0           | BP information              |
|                            | Unskilled labour wage – men                 | INR/day | 271.80 | 45.70 | 1.5           | Farmer survey               |
|                            | Unskilled labour wage – women               | INR/day | 185.10 | 36.40 | 1.5           | Farmer survey               |

Note: SD: standard deviation; BP: Biofuel program.

aINR = Indian National Rupee. 1 USD = 73.5 INR in October 2018. bRefers to the fraction of the absolute oil volume that is effectively extracted.
A discount rate of 5% is applied in Equations (6)–(10). This reflects the average real interest rate in India of the period 2011–2017 (World Bank, 2018). The real interest rate is used as parameter values are not corrected for inflation in the profitability calculation (see Section 2.2.4).

2.2.4 Data and parameters

Data were collected from a variety of sources. First, a farmer survey was implemented in the period August 2015 – May 2016 with 391 households in 36 villages throughout Hassan district. A quantitative structured questionnaire was used to collect data on pongamia cultivation, on farm production, marketing and assets, and on employment and income. Furthermore, a yield project was implemented during the pongamia harvest season from February to May in 2016. Fruit and seed yields were measured for 81 pongamia trees, aged between 5 and 60 years, sampled across Hassan district. Next, the BP provided additional information on pongamia yield, cultivation, processing and marketing features in November 2017. Finally, remaining data were derived from interviews with nine local experts, including industrial processors and agricultural scientists, in November 2017.

These data were used to assign values to an extensive set of parameters determining revenues, costs, and labour and land figures in Equations (1)–(5), and to calculate opportunity costs of labour and land. Stochastic input parameters are listed in Table 2 and nonstochastic input parameters in Table 3. The former are all assumed to be normally distributed, yet the distributions are symmetrically bounded in terms of the amount of standard deviations values can differ from the mean. All distributions are considered independent, except for the long-term yield figures; the corresponding correlation matrix can be found in Table S2.

Parameter stationarity

Collected data represent the actual on-field situation from 2015 to 2017. However, there is no additional information on how parameter values might evolve over time. Therefore, these data are used for parametrization in each simulated year. In other words, the values of stochastic parameter distributions (Table 2), nonstochastic parameters (Table 3), and opportunity costs of labour and land, do not change over the simulation period. The only exception to this is the fruit/seed yield parameter, for which the temporal pattern is explicitly modelled.

Tree cultivation parameters

Tree cultivation parameters are provided in Table 3. Field preparation is assumed to be done using tractors, whereas seedling planting is done manually. In the BP, seedling production and provision are financed by external subsidies, and correspondingly no seedling costs are considered. Furthermore, minimal management inputs are assumed: limited irrigation, no weeding, no fertilization, no pruning and no pest control – as there are no quantitative data on how yield responds to increased management inputs (Murphy et al., 2012). This largely corresponds with traditional pongamia management practices.

Yield and collection parameters

Pongamia trees usually start yielding after 5 years. Fruits consist of a hard shell encompassing one or two seeds. The seeds generally have an oil content between 30% and 40% (Table 2). Fruit and seed yields are vital parameters for profitability, yet their temporal pattern is highly variable and uncertain, and very little is known on the role of genetic and (a)biotic factors (Abadi et al., 2016;Gunatilake, 2011; Karmee & Chadha, 2005; Murphy et al., 2012; Rao, Shanker, Srinivas, Korwar, & Venkateswarlu, 2011). The BP’s data on superior local accessions differ greatly from the yield project’s data on a more random set of trees. Therefore, two distinct yield scenarios are defined: a high yield scenario based on the former, and a low yield scenario based on the latter. These cover the yield range commonly reported in literature (Abadi et al., 2016; Gunatilake, 2011). Table 2 contains the corresponding yield figures at stabilization; the entire temporal pattern is listed in Table S1, and Table S2 provides yield correlations. Notice that the BP data are markedly higher, even though these concern seed yields, whereas the yield project data are based on fruit yields.

In addition, there is a complex relationship between fruit yield and fruit collection rate. Fruits are typically harvested manually by shaking branches and collecting fallen fruits on sheets, while remaining fruits are beaten off using long poles. As tree canopies grow they produce more, yet they are generally also more difficult to handle. As a result, collection rates do not necessarily increase with tree age. However, for a given canopy size, collection rates increase with fruit density. In other words, it can be assumed that collection rates are constant over time within both yield scenarios, but higher in the high yield scenario as compared with the low yield scenario. This is taken into account through a multiplication factor (Table 2).

Processing, price and wage parameters

The relevant processing parameters depend on the value chain (Table 1), as do the values used for them (Tables 2 and 3). Pongamia fruits, seeds, seed oil and seed cake are commodities for which traditional markets exist, while the BP also functions as a market actor. Their prices in Table 2 reflect actual values in the region. The price of biodiesel is set equal to the prevailing pump petrodiesel price. Finally, gender-specific unskilled labour wages as reported in the farmer survey are used (Table 2).
Farm typology and opportunity costs
The surveyed households are spread across small, well-connected rural villages. These nuclear households derive income from a range of activities, although farming is usually their main income source. Farmers typically cultivate a few major crops on landholdings between 0.5 and 2 ha, although few of them have landholdings of tens of hectares. Correspondingly, there is large variation in income and in opportunity costs among the surveyed farmers. The return to labour of current on-farm activities, return to labour of current off-farm activities, and return to land of current farm activities are calculated for the 391 households of the farmer survey.

2.2.5 | Profitability calculation
For each combination of value chain scenario and yield scenario, 50,000 Monte Carlo samples are drawn using UQLab (Marelli & Sudret, 2014), and profitability outcomes are calculated and visualized in Stata 14 (StataCorp, 2015). The corresponding code files have been uploaded to a public GitHub repository; its weblink is included in the Supporting Information.

2.2.6 | Implementation of sensitivity analysis
Sensitivity analysis through correlations assumes the stochastic input parameters to be mutually uncorrelated.
However, there is a complex correlation between yield scenarios, individual fruit and seed yield parameters, seed/fruit mass ratio, and the fruit collection rate (see Section 2.2.4). In order to achieve uncorrelated input parameters, the following measures are taken. First, seed yield parameters are not considered, as they are entirely defined by combining fruit yield parameters and the seed/fruit mass ratio. Second, the yield scenarios are not considered; rather a principal component analysis is applied to the fruit yield parameters to construct an indicator for the overall yield level within each Monte Carlo run. Third, the seed/fruit mass ratio and the fruit collection rate are added to this principal component analysis, in an effort to separate the variance they share with the fruit yield parameters from their own specific variance.

3 | RESULTS

3.1 | Profitability for farmers

The probability distributions of the net present returns to family land for farmers are displayed in Figure 1. In case of family labour (Figure 1a,b), net present returns to land are positive for all value chain scenarios but sensitive to the yield scenario: they rise to one million INR/ha for the low yield scenario, whereas the double could be reached in case of high yields. Although substantial variation obscures the relative performances of different value chain scenarios, the distinction becomes more clear-cut by comparing them within the same Monte Carlo runs (Table S3): community processing (= farmer-oil chain) entails higher returns to land than seed selling (= farmer-BP/industry chains), which in turn outperforms fruit selling (= BP chains). This also arises from the median return to land trajectories (Figure 2a,b). Returns to land become positive once the trees start yielding, yet it takes considerable time before the yield becomes substantial enough so that the median return to land of current on-farm activities (65,000 INR/(ha*year)) is achieved. In the low yield scenario this median return is only reached in case of community processing, and even then only after 18 years. In the high yield scenario it is reached in all value chains scenarios, after 8, 10 and 17 years for community processing, seed selling and fruit selling, respectively, although long-term returns to land are substantially higher.

If labour is hired, however, pongamia cultivation might not have positive returns to family land at all (Figure 1c,d). Seed selling chains perform worst in this case, with positive figures in only 40%–43% of the Monte Carlo runs in the low yield scenario, and in 57%–60% in the high yield scenario. Community processing leads again to the highest returns to land, while fruit selling is now situated in-between (Table S3): in these chains positive returns to land are realized in 76%–82% of Monte Carlo runs in case of low yields, and 93%–97% for high yields. Figure 2c,d illustrates that the median returns to land of cultivating pongamia are marginal if labour is hired. A return to land of 65,000 INR/(ha*year) is only attained in case of high yields and community processing, and even then only after 19 years.

Returns to family labour of pongamia cultivation are generally less sensitive to the yield scenario (Figure 1e,f). Yield is only important for the fruit selling chains, which have the highest return to labour among the value chain scenarios (Table S3). Returns to labour quickly stabilize after yield initiation at 24–27 INR/hr for seed selling and at 34–38 INR/hr for community processing (Figure 2e,f). This is higher than the current on-farm return to labour for 63%–67% and 73%–75% of the surveyed households, respectively. Competitiveness with off-farm activities is markedly lower, however. If fruits are sold, returns to labour equal 40 INR/hr at stabilization for the low yield scenario and 60 INR/hr for the high yield scenario, surpassing current on-farm return to labour for 77% and 85% of the surveyed households, respectively.

Figure 3 provides a combined assessment of the impacts pongamia cultivation has on returns to labour and to land – in case of cultivation with family land and family labour – in comparison with other farm activities. The graphs consider the fraction of farmers for whom both median returns are higher in pongamia cultivation than in their current on-farm activities, i.e., for whom pongamia cultivation is certainly profitable, and display how this fraction evolves over time. In both yield scenarios the curve rises sharply between 5 and 10 years, after which it gradually levels off. In the low yield scenario, stabilization takes place at a fraction of 30% for fruit selling, 41% for seed selling, and 54% for community processing. In the high yield scenario, profitability is eventually reached for 6 of 10 farmers if they sell seeds or fruits, and for 7 of 10 farmers if they process themselves.

3.2 | Profitability for processors

The probability distributions of the net present profits for processors, as well as the median profit trajectories, are shown in Figure 4. For current processing features and price structures, it is unambiguously more rational to sell seed oil, rather than to convert it to biodiesel (Table S4). In fact, while the former is most likely a lucrative activity, profitability of the latter is highly uncertain (Figure 4a,b). The oil value chains have positive outcomes in 83%–97% of the Monte Carlo runs, and profits become substantial after an initial lag period, especially in the high yield scenario (Figure 4c,d). Biodiesel conversion in the Biofuel Park is only viable in 22% of the runs when fruits are bought and in 34% in case of seed buying. This figure...
increases to 62% for industrial processing, although profits remain very limited.

3.3 | Sensitivity

Variability and uncertainty in the stochastic input parameters cause substantial variation in estimated profitability measures, as illustrated in Figures 1 and 4. Before exploring this in the sensitivity analysis, the results of the principal component analysis on the fruit yield parameters, seed/fruit mass ratio and collection rate are considered. As expected, it allows to separate the specific variances of each of these three features. All eigenvectors and variance contributions are presented in Table S5. The first component explains 80% of the variance and can be considered an overall yield indicator; its correlations with the individual fruit yield parameters are all above 0.81. The second and third component have relatively high loadings from the seed/fruit mass ratio and the collection rate, respectively, and are correspondingly interpreted as their proxies; respective correlations are 0.90 and −0.70. To facilitate interpretation, the opposite of the third component will be used. By using these three principal components in the sensitivity analysis instead of the original variables, all input parameters can be considered uncorrelated; all absolute correlations are in practice below 0.02.

The contributions of the stochastic input parameters to the variation in outcomes are shown in Figure 5. First, an overall yield increase can strongly stimulate profitability: for farmers especially if family labour is used (Figure 5a), and for processors in those value chains that have predominantly positive outcomes (Figure 5d). Similarly, heavier seeds enhance profitability: for farmers most strongly in case of community processing and seed selling, for processors in case of fruit buying. Oil content is less important, and the contribution of the collection rate is also relatively limited, except for the returns to labour of fruit-selling farmers (Figure 5c). Second, variability and uncertainty in processing parameters generally have very marginal effects on profitability, even for processors. Only the deshelling rate significantly influences farmers’ returns to labour (Figure 5c), or equivalently the return to land if labour is hired (Figure 5b), as well as BP profits (Figure 5d). Third, price structures play a major role in profitability. An increase in feedstock prices enhances profitability for farmers while it negatively affects processors’ profitability. Similarly, an increase in end product prices enhances profitability for processors, and for farmers in case of community processing. Labour wages negatively affect farmers’ profitability in case labour is hired, in particular female labour wages (Figure 5b).

3.4 | Optimization scenarios

In accordance with the results from the sensitivity analysis, three features are considered to have major potential for improving profitability: yield, deshelling rate and price structure. Uncertainties on current yield values and on their interaction with associated parameters (seed/fruit mass ratio and collection rate), are substantial, however (see Section 2.2.4). Therefore, increasing the yield even beyond the high yield scenario seems little useful. Achievable yield patterns are at least in the short term likely situated in between both
yield scenarios. Correspondingly, the optimization scenarios use a medium yield scenario calculated as an average of the low and high yield scenarios; the entire yield pattern is provided in Table S1. The collection rate multiplication factor from Table 2 is maintained, except for its mean value, which is set to 1.33.
The optimization scenarios explore the potential of the other two features. First, they fix all processing parameters at their mean – except for the deshelling rate – and only use the medium yield scenario. Next, for each of the fruit, seed, oil and biodiesel price parameters, a discrete set of fixed values is defined. Each of these four sets is separately used to replace the corresponding stochastic price parameter with a fixed value in the model, and for each fixed value 10,000 Monte Carlo iterations are run. The probability distributions of the net present returns to land for farmers – if labour is hired – as well as the probability distributions of the net present profits for processors, are estimated and the 10th percentiles are plotted. This allows to determine the value at which these measures becomes positive with a probability of at least 90%. Finally, for farmers these simulations are also run for a hypothetical situation in which deshelling is mechanized at the village level. The corresponding deshelling rate is assumed to be normally distributed with a mean of 25 kg fruits per hour per person, a $SD$ of 3 and symmetrically bounded at 1 $SD$ from the mean. Electricity costs and deshelling losses are assumed to be fixed at 24.5 INR/hr and 20%, respectively.

The results are displayed for the relevant value chains in Figure 6. In what follows, the concepts “positive returns to land with a probability of at least 90%” is briefly worded as “positive returns to land.” Similarly, “positive profits with a probability of at least 90%” is briefly worded as “positive profits” or “profitable.”

In case of community processing (= farmer-oil chain), only farmers are involved and oil is the end product (Figure 6c). The value chain has positive returns to land for farmers at an oil price around 67 INR/L, which is close to its current mean value. However, in case of mechanical deshelling, positive returns to land are already reached before the start of the modelled range (42 INR/L).

In case of fruit selling chains (= BP chains), the fruit price range within which the oil value chain has both positive returns to land for farmers and positive profits for the BP, is roughly between 6 and 6.5 INR/kg (Figure 6a), which is near its current value. In contrast, the biodiesel value chain becomes only profitable for the BP below 3
INR/kg, which is infeasible for farmers. With current fruit prices, biodiesel prices need to increase above about 116 INR/L for this value chain to become profitable for the BP (Figure 6d).

In case of seed selling chains (= farmer-BP/industry chains), at current seed prices processor profitability is reached in the oil value chains around 57–64 INR/L oil, which is below its actual price (Figure 6c). Biodiesel value chains would require a price of 78–98 INR/L, however (Figure 6d). Moreover, farmers actually require a much higher seed price of about 28 INR/kg for positive returns to land (Figure 6b). At current oil and biodiesel prices, this scenario would put oil-selling processors at the brink of viability, while for biodiesel-selling processors it is definitely not viable (Figure 6b). The latter would require a further biodiesel price increase up to 89–110 INR/L for profitability. If village-level mechanical deshelling is introduced, conditions are substantially relaxed (Figure 6b). In this case, there is common support for farmers and processors in the oil value chains at a seed price range between 19 and 26 INR/kg. Even biodiesel selling would be profitable for industrial processors and farmers at a seed price range between 19 and 20 INR/kg.

4 | DISCUSSION

4.1 | Interpretation of results

The application of the profitability framework demonstrates that variability and uncertainty in input parameters strongly propagate, leading to substantial variation in calculated outcomes. Taking this into account, on the one hand, is considered a strength of the framework. The lack of formal uncertainty analysis is one of the methodological shortcomings in many biofuel profitability studies. The stochastic approach used in the framework shows that it is crucial to consider variability and uncertainty, as different sets of parameter values might imply different conclusions. Relying on deterministic models might lead to oversimplified and possibly misleading results, which are only revealed through reviews such as van Eijck et al. (2014). On the other hand, the uncertainty analysis reveals a limitation of the application to the case study. Remaining uncertainty on several input parameters translates to considerable uncertainty on profitability measures as well, hence warranting sufficient caution when stating conclusions. Nevertheless, the analyses in the application allow identifying several trends and key findings.
Since activities such as fruit collection and deshelling make the biofuel value chain very labour intensive, its profitability and optimal configuration for farmers strongly depend on labour allocation and opportunity costs. If pongamia cultivation requires expensive wage labour, such as in commercial settings, excessive labour costs severely constrain profitability, as they do for jatropha (Borman et al., 2013; van Eijck et al., 2014). This is confirmed by survey results on current practices, which show that only 5% of fruit-collecting households hire labour for collection. If pongamia can be cultivated using exclusively family labour, by planting only on a limited area, it may become profitable. More specifically, profitability is guaranteed if returns to both labour and land are higher for pongamia cultivation than for current farm activities. Applying this decision rule, the results show that engaging in pongamia cultivation is usually only fruitful in the middle to long term, and only for at most one of two farmers in the low yield scenario. In the high yield scenario, this fraction increases to 60%—70% of farmers. Among them, labour-constrained farmers would look for the value chains with highest return to labour, which prove to be those with least farmer involvement, namely fruit selling. Land-constrained farmers would prefer the value chains with highest return to land, which are, conversely, those with highest farmer involvement, namely community processing. Overall, community processing is profitable for the highest share of farmers.

These key profitability outcomes for farmers raise three additional discussion points. First, the comparatively low returns to labour and land of pongamia cultivation for a substantial share of farmers, were identified as major adoption barriers for the BP by Dalemans et al. (2019) and de Hoop (2017). Opportunity costs of labour and land simply cannot be ignored in profitability studies (Borman et al., 2013; Van Eijck, Smeets, & Faaij, 2012), and income from these biofuel systems cannot be considered as purely additional. For this reason, the substantial income gains that are predicted for the same BP by Bohra et al. (2016) are clearly exaggerated.

Second, there appears to be most potential for decentralized processing and local value addition schemes, which is in line with recommendations from Achten, Maes et al. (2010),...
Lokesh et al. (2015), Muys et al. (2014) and Sharma et al. (2016). Decentralization at village level entails more employment opportunities and allows farmers to use processed products themselves, such as seed cake against nutrient loss. However, Dalemans et al. (2019) find very few evidence that processing at village level effectively occurs in Hassan district. Despite many efforts of the BP, in reality this value chain in particular likely still suffers from a lot of imperfections (see further in Section 4.24.2). Third, it should be noted that while substantial returns to labour and especially land are only realized after several years, investments in cultivation are already required in the first few years. This revenue lag and associated investment risk is inherent to many perennial-based systems (Alexander et al., 2012; Khanna, Zilberman, & Miao, 2017). It remains questionable whether farmers are willing to wait for over 5–10 years until these systems become profitable, especially the most poor and risk-averse ones. Several studies have suggested that contract-farming models might decrease future marketing and hence investment risk (Dalemans et al., 2018; Shepherd, 2013). Revenue lags are also crucial for processors: large initial investments are required, while feedstock provision is limited for several years, and the risk of farmers quitting cultivation is directly passed on to processors.

While the optimal value chain configuration for farmers is to some extent ambiguous, for processors oil selling is clearly more lucrative than converting it to biodiesel. This directly results from oil prices being usually higher than biodiesel prices (Table 2) and reflects the current market reality in which oil is used in various industries, whereas the biodiesel value chain is practically nonexistent (Dalemans et al., 2019; de Hoop, 2017). More generally, this study shows that price structures are key to realizing profitability for all value chain actors, and that this mechanism can only be fully explored by taking all actors into account. Oil value chains likely have positive returns to land for farmers using wage labour and positive profits for processors under current oil prices. However, this is certainly not the case for biodiesel value chains, which require a substantial increase in biodiesel price for common support. Even though local pump petrodiesel prices have risen in 2018 to 65–75 INR/L, this level is still below the required biodiesel factory gate price ranges of 98–116 INR/L for the BP and 78–89 INR/L for industrial processors. Moreover, this study does not consider the effects of distribution and retail, fiscal and marketing policies, and differences in energetic values. Including these factors would generally reduce biodiesel competitiveness even more (Kumar, Chaube, & Jain, 2012; Lokesh et al., 2015; Pohit & Biswas, 2017). Petrodiesel price volatility implies that price increases might be more likely for biodiesel than for oil, but also that marketing risks are higher, especially in these perennial systems (Tuli & Gupta, 2017). In any case, the results indicate that price support is currently indispensable for biodiesel value chains. As a subsidiary measure, it has more impact than input support such as seedling provision: if the latter has to be paid for by farmers or processors, its impact on the net present profitability measures is offset by an increase of only 1.1–1.7 INR/L in the oil or biodiesel price.

An alternative strategy to achieve overall value chain profitability would be technological innovation and infrastructural investment. Fruit deshelling proves to be an important bottleneck for the value chain. Complementing expelling equipment with mechanical deshelling at village level would greatly improve labour productivity, in spite of increased seed losses. In turn this would strongly relax the end product price increases needed for overall profitability. Of course this innovation would require either substantial subsidiary support or village repayment schemes, the financial feasibility of which should also be investigated. Moreover, the development of effective deshelling equipment is technically challenging. Interestingly, labour productivity is already improved through another, technically straightforward “innovation”: the use of sheets for fruit collection. This study considers this practice as the default, yet 42.5% of the surveyed, fruit-collecting households collects fruits by manually picking them from the ground, as tree climbing is not always possible (see also de Hoop, 2017). Collection rates are substantially lower in this case, which has major implications for profitability as well (see Figure S1, compared with Figures 1 and 2). This might partly explain low profitability claims reported by Dalemans et al. (2019). Labour constraints might be further relaxed by mechanized harvesting, but this requires further technological developments (Murphy et al., 2012).

Finally, in addition to price structures and mechanization, yield proves to be crucial in determining returns to land. Yield is primarily important for farmers, yet for processors it should also be considered. This is because it determines the area required for providing a given feedstock mass, and in turn the logistics involved—a relationship that has not been modelled in this study, but which might partly compensate economies of scale (see for example Borman et al., 2013). For instance, one hectare produces on average 730 L of oil in the low yield scenario, while this production almost triples to 2,031 L in the high yield scenario. Despite the use of primary yield data in this study, there remains a critical knowledge gap on how genetic, physiological and (a)biotic factors determine pongamia yield variability across trees and years. This inevitably leads to financial risks and uncertainties, as it does for jatropha-based systems (Borman et al., 2013; van Eijck et al., 2014; Muys et al., 2014). These observations emphasize the need for further regional-specific yield research and improvement (Abadi et al., 2016; Johnston, Foley, Holloway, Kucharik, & Monfreda, 2009).
4.2 Limitations of the application

Several limitations of the application to the case study should be acknowledged, each of which might influence the findings discussed in the previous section. These limitations are briefly discussed and their potential implications are qualitatively assessed.

First, the analysis assumes perfect value chains in which there is full information, no entry or exit barriers, perfect factor mobility, guaranteed feedstock marketing channels for farmers and continuous feedstock provision for processors. The latter allows investing in mechanization and infrastructure, and thereby realizing economies of scale. However, Dalemans et al. (2019) and de Hoop (2017) show that these conditions do not apply to the biofuel value chain in Hassan district. Similarly, the analysis assumes optimal practices and conditions for cultivation and processing. This is also not always the case in reality: frequently occurring examples include limited seedling survival, equipment malfunctions and hampered collection due to lack of weeding and collection sheets. Imperfect value chains, practices and conditions will increase risk, inefficiencies and transaction costs, and will reduce factor productivity, profitability and adoption. These issues might be mitigated by horizontal or vertical coordination of the value chain, such as associations or contract farming (Dalemans et al., 2018; Negash & Swinnen, 2013; Riera & Swinnen, 2016; Shinoj et al., 2010).

Second, the stationarity assumption in parameter values is a critical limitation. The 30-year calculation period likely implies substantial temporal changes in parameter values. However, the relative parameter changes are very complex to predict, and so is their combined effect on profitability. For example, increased mechanization within the pongamia value chain might be offset by increased opportunity costs and labour wages, resulting from agricultural innovations or structural transformation.

Finally, the analysis focuses entirely on financial outcomes, without quantifying ecological and social impacts. In particular, whereas the functional unit in the analysis is a pongamia monoculture, the actual focus of the BP is on agroforestry systems in which trees are integrated (in small numbers) within existing land uses. This approach explicitly emphasizes the diversity in uses and benefits the trees provide. The extent to which these features affect overall system productivity and welfare outcomes is not well-documented. Knowledge on ecosystem (dis)services is limited (Gasparatos, Stromberg, & Takeuchi, 2011), yet as a nitrogen-fixing tree pongamia might have considerable potential (Biswa, Scott, & Gresshoff, 2011). Nevertheless, some insights can be listed on financial outcome differences in agroforestry set-ups. First, profitability will increase if accounting for other tree uses, e.g., construction wood, leaf-based manure, medicinal and pesticidal uses. Second, returns to land could be increased by intercropping and silvopastoral arrangements, or alternatively land opportunity costs reduced by planting seedlings in marginal areas or on bunds, although this likely also influences yields. Reducing the amount of trees or cultivating them on lower value land, reduces farmers’ investment risk, which might spill over to processors. Opportunity costs of labour could also be decreased in case of fewer trees, as labour demands are reduced and could therefore be more easily allocated to leaner moments. On the other hand, fixed transaction costs will have a larger negative effect on profitability in case of fewer trees. In addition, fewer trees might limit opportunities for mechanization and economies of scale, and increase logistical costs, for self-processing communities and processors.

4.3 Generalization

The application to the case study illustrates how the evaluation framework can be used to quantify profitability of various value chain configurations for several value chain actors. Although the findings and code files (see GitHub-weblink in Supporting Information) are case-specific, the developed framework opens the door to comprehensive investigation of the financial performance of other oilseed tree species and in other regions. This allows to explore outcomes under various agro-ecological, socio-economic and institutional conditions. In addition, the framework can be flexibly adapted to include additional functionalities, such as interactions in agroforestry set-ups.

4.4 Policy implications

The BP in Hassan district has been promoting pongamia biofuel chains as a strategy for improving local energy security, and for generating additional income and employment. This profitability study strongly questions this rationale. The results show that biodiesel production is not competitive in this region with readily available and relatively cheap petroleum. Moreover, commercial pongamia cultivation with wage employment is not economically viable. Pongamia currently remains a minor cash crop for small-scale oil production by a subset of farmers. This firstly implies that for the time being the BP should primarily focus on enhancing decentralized value addition and marketing linkages for oil, rather than for biodiesel. Second, and irrespective of the end product, the Program should address the major bottlenecks for value chain profitability. Labour productivity of collection, expelling and especially deshelling practices can be improved by increasing and optimizing mechanization. Limited yields and long maturation periods can be addressed by developing fast-maturing, high-yielding and agro-ecologically adapted cultivars.

In general, the development of pongamia biofuel chains remains jeopardized by the combination of volatile fossil
fuel prices and high labour requirements, even in low-income areas. Pongamia’s potential as a source of renewable energy and ecosystem services can only be fully realized if actions are taken to increase its financial performance. Formulating fiscal and marketing policies in line with clean energy discourses is of prime importance. Furthermore, technological innovations and increased coordination across the value chain would further improve economic outcomes.

This study emphasizes the importance of several methodological concepts in biofuel profitability studies, including quantitative uncertainty analysis, consideration of actor-specific opportunity costs, and inclusion of several value chain scenarios and actors. It provides policymakers with a methodologically sound tool to calculate profitability of biofuel innovations for any predefined scenario, depending on which criteria they use to fix parameter values, and can correspondingly form a basis for more specific policy implications as well. Thereby, this study adds to the limited existing evidence on the profitability of biofuel production from oilseed trees, pongamia in particular, but it should be emphasized that many uncertainties remain. Economic and technological developments over the lifetime of an oilseed tree cultivation, interactions and socio-ecological outcomes in agroforestry set-ups, and value chain imperfections all further influence actual welfare outcomes. Further research is warranted to increase insights in these complex relationships.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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