



# Regional material flow behaviors of agro-food processing craft villages in Red River Delta, Vietnam

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[After initial online publication, the article was changed to correctly indicate the applicable legal regulation that applies to craft villages and that FPCVs is an abbreviation for "agro-Food Processing Craft Villages." Additionally, the publisher mistakenly published the wrong data openness badge and this has been corrected.]

## Abstract

The economic reform "Đổi Mới" in 1986 has rapidly increased the number of craft villages in Vietnam, especially in the Red River Delta (RRD) leading to environmental degradation. This article presents an assessment of environmental and resource issues of agro-Food Processing Craft Villages (FPCVs) in RRD using a refined approach to material flow analysis focusing on consistent quantification of uncertainty with particular attention to secondary and empirical data that are often faced in material flow analyses in transition economies. Material flows of *agro-Food Processing* including eight types of production were examined and linked to activities of private *Households*, *Rice Cultivation*, and *Pig Farming* in a model called *Red River Delta*. Materials investigated were Goods (i.e., total materials), organic carbon (org.C), nitrogen (N), and phosphorus (P). The findings reveal material cycles are almost entirely open, that is, the materials used in FPCVs do not recycle within the region. From ~10.5 million tons/year of imported Goods used for *agro-Food Processing*, final products and utilized materials account for minor fractions (~5%, by weight). Conversely, the majority (88%) is directly discharged. Materials accumulated as stocks represent 1% of Goods (100,000 tons/year), 21% of org.C (~34,000 tons/year), 42% of N (~1,300 tons/year), and 57% of P (~300 tons/year), whose substance concentrations vastly exceed natural resilience capacities. Although *agro-Food Processing* accounts for negligible material shares in *Red River Delta*, FPCVs pollution is severe at local levels due to the location of home-based production. Several options for closing material loops at various system scales are recommended for environmental and resource management of FPCVs. The material flow analysis results provide a database that may be used as a decision support tool for production establishments in craft villages and relevant authorities in setting priorities on environmental planning and resource management. This article met the requirements for a gold – silver JIE data openness badge described at <http://jiec.click/badges>.

## KEYWORDS

craft villages, data uncertainty analysis, industrial ecology, material flow analysis (MFA), Red River Delta, transition economies

## 1 | INTRODUCTION

### 1.1 | Agro-food processing craft villages in Red River Delta

Craft villages are characterized by more than 20% of craft production households operating in a stable condition for at least 2 years and obeying environmental legislation (52/2018/NĐ-CP, 2018). In this study, agro-Food Processing Craft Villages (FPCVs) refer to craft villages processing foods from raw agricultural products. FPCVs are mainly located in RRD (39/BC-UBTVQH13, 2011; Chi, 2005; Fanchette, Stedman, Carlet-Soulages, & Digregorio, 2010; GSO, 2012; Sakata, 2010, 2013; Thạch, 2006; WB, 2012). They have a long tradition and are the most common type

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of craft villages in Vietnam (Chi, 2005; MONRE, 2008; Sang, 2010). The economic renovation “*Đoi Moi*” in 1986 and Resolution V in 1993 have significantly increased the number of craft villages to mitigate poverty and foster rural industrialization (Chi, 2005; Sakata, 2013), leading to a trade-off as alarming environmental pollution in rural areas, notably from the end of the 1990s (own synthesis based on: Perrings, 1998; Chi, 2005; CTIC, 2008; Đam, Anh, Hien, Long, & Trung, 2004; JICA-MARD, 2004; KEI-WB, 2002; Kim, 2005; Konstadakopoulos, 2008; MONRE, 2008). Three major problems in FPCVs are huge fresh water consumption and wastewater generation, organic and nutrient contamination, and secondary pollution from animal raising (own survey and synthesis based on Chi, 2005; MONRE, 2008; Sang, 2010; Mahanty, Dang, & Phung, 2010; Meier, 2016). Sadly, these issues remain largely unsolved because of the less proactive responses, which are more toward instant solutions rather than eliminating the root causes.

In particular, most studies focused on wastewater treatment technologies (e.g., Phuoc, 2003; Chi, 2003; Truyen, 2004; Chi, 2005; CTIC, 2008; Sang, 2010; Da, Dufour, Marouze, Le, & Marechal, 2008; Thuy, 2011; Hahn et al., 2012; Hahn, Lorbeer, & Nguyet, 2015; Holger, Appel, 2015) and solid residue processing (e.g., Meier, 2016; Nguyen & Chu, 2012; Sang, 2010). However, research outcomes are rarely applied. Material flow analysis (MFA) is utilized simply to recommend treatment techniques and cleaner production (e.g., Phuoc, 2003; Chi, 2003; Chi, 2005; Da et al., 2008; Sang, 2010; Da et al., 2013), but often performed superficially. Particularly, MFAs were mostly investigated at small scales (i.e., individual household production processes) and for Goods (i.e., total materials) rather than substances. These views are insufficient to fully identify material utilization potentials and reflect critical problems majorly contributed by substances (Brunner & Rechberger, 2016). Until recently, Meier (2016) studied flows of energy, Goods, nitrogen (N), phosphorus (P), and organic carbon (org.C) of a liquor processing village. Although extensive, the “hotspots” (i.e., flows, processes) triggering environmental and resource issues were not pinpointed. Altogether, the contemporary research needs to be complemented by a more holistic view of material flow systems.

Besides, the Vietnamese government has acted against environmental pollution in craft villages. Good examples of this are the obligatory relocation of seriously polluting production establishments to village production zones (64/2003/QĐ-TTg, 2003; 55/2014/QĐ-HCT, 2014; 26/2015/TT-BTNMT, 2015; 31/2016/TT-BTNMT, 2016; 68/2017/NĐ-CP, 2017), requirements of environmental planning and monitoring (19/2015/NĐ-CP, 2015). Nevertheless, the enforcement is weak because it is too ambitious for craft villages to meet strict environmental regulations (e.g., 51/2014/TT-BTNMT, 2014; 154/2016/NĐ-CP, 2016) originally designed for industries (Chi, 2005; MONRE, 2008; Loi, 2013; Hai, Schnitzer, Van, Thao, & Braunegg, 2016). Buffer steps with specific technical guidelines are thus necessary to assist production establishments in gradually conforming to environmental requirements.

A robust MFA can substantially fulfill scientific gaps and facilitate the implementation of environmental regulations in FPCVs. In this regard, the following analyzes relevant MFA aspects.

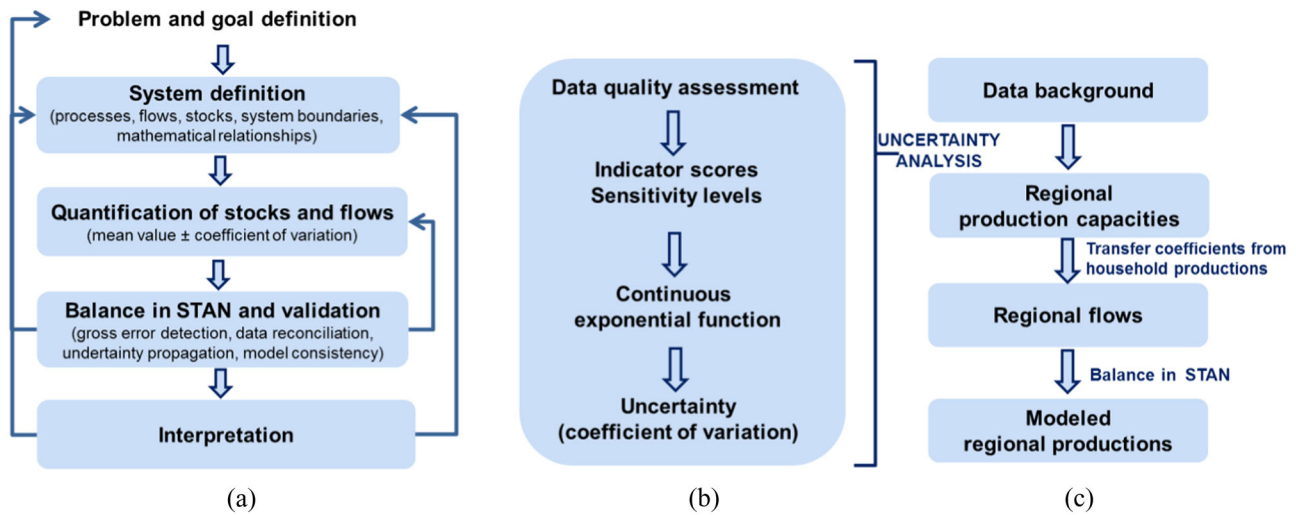
## 1.2 | Advanced material flow analysis and nutrient flow management

### 1.2.1 | Importance of data uncertainty analysis in MFA

MFA refers to material flow assessment concerning sources, pathways, and stocks in a system defined by spatial and temporal boundaries (Brunner & Rechberger, 2016). MFA is a recognized decision support tool for environmental and resource management. The increasing application of MFA demands more advanced techniques to achieve rigorous results (Laner, Rechberger, & Astrup, 2014; Rechberger, Cencic, & Fruhwirth, 2014) leading to a growing focus on data uncertainty analysis. More specifically, data uncertainty is an inherent MFA characteristic (Cencic, 2004; Laner et al., 2014; Schwab, Zoboli, & Rechberger, 2017) and should be included since the nowadays MFA software automates many calculations (Rechberger et al., 2014). Surprisingly, not many studies have reported data uncertainty (Danus & Burstrom, 2001; Danus, 2002; Laner et al., 2014). Data uncertainty analysis offers a solution to data limitations, especially in the developing country circumstance (Montangero, 2007; Binder, 2007; Schaffner, 2007; Do-Thu et al., 2011). Concretely, it helps to detect gross errors (i.e., data conflict due to errors in empirical measurements or other sources (Narasimhan & Jordache, 1999) in a system of redundant information and solvable equations and subsequently reconcile inconsistent values (Cencic, 2004, 2016a, 2016b). Moreover, a systematic data characterization for uncertainty analysis delivers a transparent message of study outcomes (Schwab, Rechberger, & Holnsteiner, 2016; Schwab et al., 2017).

### 1.2.2 | MFA studies on nutrients

In industrialized countries, MFAs of nutrients are widely applied and predominantly focus on P for conservational purposes (e.g., Ott & Rechberger, 2012; Kalmykova, Harder, Borgstedt, & Svanang, 2012; Klinglmair et al., 2015; van Dijk, Lesschen, & Oenema, 2016; Mehr, Jedelhauser, & Binder, 2017). Conversely, developing countries are primarily impacted by organic and nutrient pollution. MFA practice has been considered less feasible, especially at regional scale, because of poor data availability (Binder, 1996; Montangero, 2007). Nevertheless, with methodological advancement, MFA studies have been gradually realized, such as in Thailand (e.g., Schaffner, 2007), Vietnam (e.g., Montangero, 2007; Aramaki & Thuy, 2010; Do-Thu et al., 2011; Nguyen et al., 2013; Do & Nishida, 2014; Meier, 2016), Ethiopia (e.g., Meinzinger, 2010), Colombia (e.g., Binder, 1996), Nicaragua (e.g., Pfister, Bader, Scheidegger, & Baccini, 2005), and Mexico (e.g., Gutierrez, 2016). In Southeast Asia, two of the earliest probabilistic MFAs applying modeling concepts from Baccini & Bader (1996) and data uncertainty analysis were performed by Montangero (2007) for municipal sanitation



**FIGURE 1** Applied modeling procedure for material flow systems: a) General framework (adapted from Brunner and Rechberger (2016)), b) Concept of data uncertainty analysis (modified after Laner et al. (2016)), c) Upscaling of productions

system in Hà Nội, Vietnam and by Schaffner (2007) for the Thachin River Basin, Thailand. Their findings inspired other regional MFAs in Vietnam, such as Aramaki & Thuy (2010), Do-Thu et al. (2011), Do, Trinh, & Nishida (2014), Do & Nishida (2014), Pham, Harada, Fujii, Nguyen, & Huynh (2017). However, only Do-Thu et al. (2011), Do et al. (2014), Do and Nishida (2014) included data uncertainty but lacked consistency and data quality assessment. For MFA studies on FPCVs, data uncertainty has not yet considered. Correspondingly, a systematic data uncertainty analysis is required to achieve robust MFA results.

### 1.3 | Objectives

As regards the above analyses, this study first aims to address environmental and resource challenges in FPCVs in RRD with a holistic view of material flows for Goods, org.C, N, and P. The MFA results are expected to provide an in-depth and transparent database as a decision support tool for production establishments and relevant authorities in setting priorities on environmental planning and resource management. Another goal is to refine techniques of data uncertainty analysis to overcome specific data limitations in MFA, particularly in the situation of transition economies.

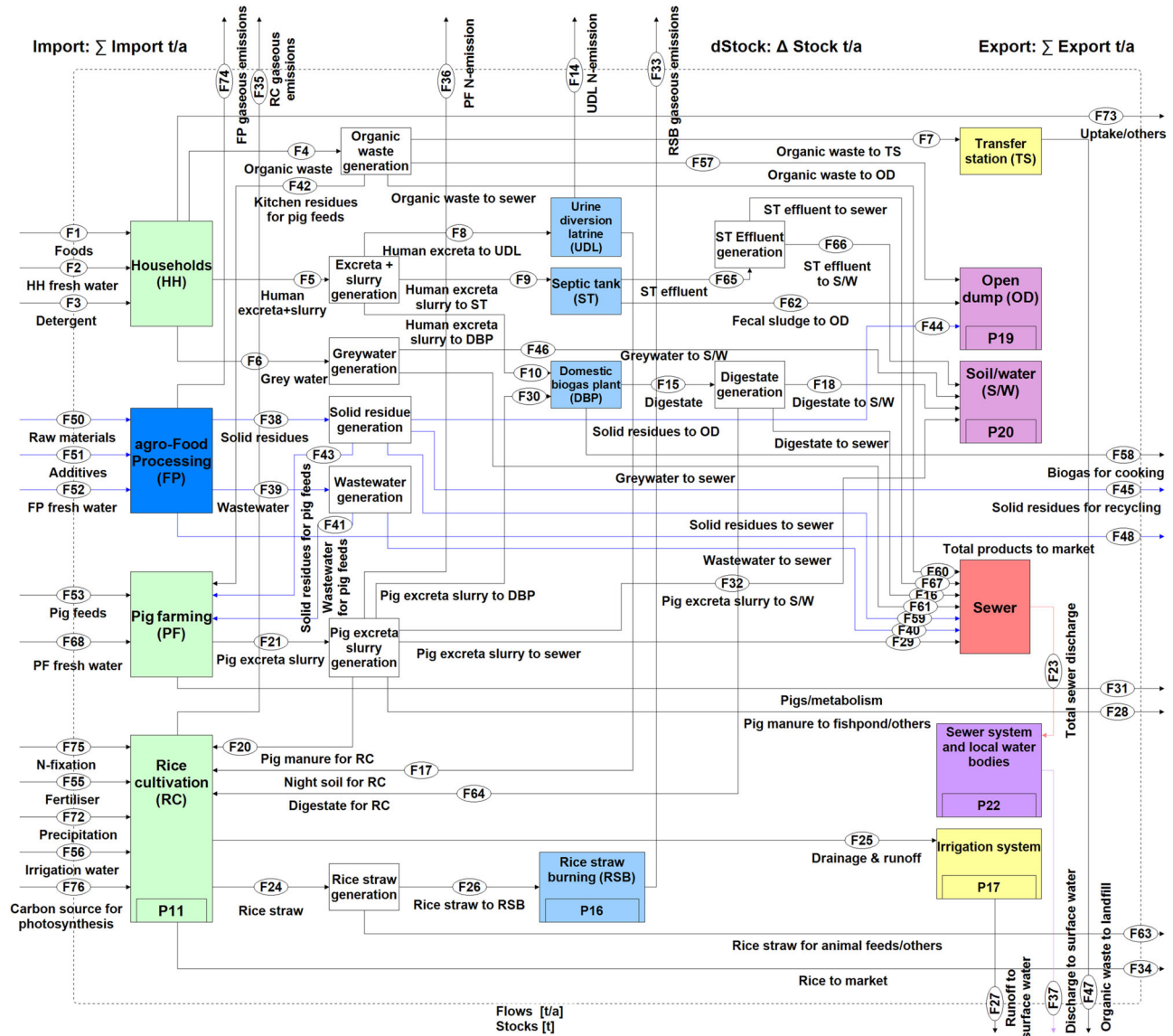
## 2 | METHODS

### 2.1 | General framework

This study adapts the concept of statistical MFA from Brunner and Rechberger (2016), emphasizing the data uncertainty analysis modified after Laner, Feketeitsch, Rechberger, and Fellner (2016) and upscaling of production from household to regional level of RRD (Figure 1).

### 2.2 | System analysis

Processes, flows, stocks, and indicator materials are sufficiently included into system *agro-Food Processing* conforming with defined problems and goals (see Section 1.1). In this respect, *indicator materials* are Goods, org.C, N, and P. Additionally, COD (Chemical Oxygen Demand), TS (Total Solids) are investigated to evaluate other discharge properties. The *agro-Food Processing* consists of production steps but not raw material cultivation and product consumption. It is interlinked with *relevant processes* including private *Households*, *Rice Cultivation*, and *Pig Farming*, forming the overall system *Red River Delta* (Figure 2). *Households* describe metabolism of rural households regarding blackwater, grey water, and organic waste. *Rice Cultivation* and *Pig Farming* represent activities of crop cultivation and livestock farming, respectively. While over-application of chemical fertilizer and uncontrolled burning of rice straw are critical issues for *Rice Cultivation*, mismanagement of pig manure from *Pig Farming* creates secondary pollution. *Temporal boundary* is the year 2015. *Spatial boundary* is the rural RRD. Gaseous emissions are considered out of the system boundary. No municipal wastewater and solid waste treatment facilities were included since they almost did not exist or were under construction by the time of investigation. Landfills were excluded because they are usually located far from residential areas and their sophisticated metabolism is beyond the scope of this work. Key determinants of stocks (i.e., materials accumulated in a process) are the spatial distribution of emissions from living



**FIGURE 2** Relationship of *agro-Food Processing* (FP) and activities of private *Households* (HH), *Rice Cultivation* (RC), and *Pig Farming* (PF) in *Red River Delta* in 2015. UDL, Urine Diversion Latrine; ST, Septic Tank; DBP, Domestic Biogas Plant; S/W, Soil/Water; RSB, Rice Straw Burning; F, Flow; P, Process. The rectangle inside a process symbolizes stocks. Units: t, tons; a, annum. Tons refer to metric tons

settlements and observable impacts on human health and nature. Therefore, open dumps, sewer systems, and local environmental compartments and/or water pathways are considered processes containing stocks. For simplicity's sake, all materials discharged untreated become stocks. However, for the sewer system and local water pathways, Goods' stock is generally calculated as the accumulated TS. For *Rice Cultivation*, stocks include also water penetrating into the field soil. Surface water refers to the natural water body located far from residential areas and suffering trivial environmental impacts; thus its substance contents are assumed zero. For simplification, substance contents in rainwater, bored-well or tap water, and irrigation water are not considered because of the negligible amount compared to artificial sources and dynamic metabolisms of historical substance accumulation in irrigation system. Qualitative behaviors of *Red River Delta* are illustrated in Figure 2, mathematical relationships and flow and stock values are found in Supporting Information S8 (descriptions in S8.1; Table 19 in S8.3).

### 2.3 | Quantification of stocks and flows and balance of system

Flows and stocks are expressed as mean value and relative standard uncertainty estimated using primary and/or secondary data. Gross errors are eliminated and systems are balanced within software STAN version 2.6.801 (Cencic & Rechberger, 2008, <http://stan2web.net/>). *Agro-Food Processing* and relevant processes are modeled individually before integrating into *Red River Delta*. Models are validated after revising consistency

and reasonability by comparing calculated values with empirical and/or literature data. Further details are provided in Supporting Information S2 (Tables 4, 5), S4.2 (Table 8), S5 (Table 11 in S5.1; descriptions in S5.2, S5.3), and S8.2 (Tables 15a, 16a, 17a).

## 2.4 | Concept of data uncertainty analysis

Under assumption of normality and independent variables, the data uncertainty analysis follows a concept modified after Laner et al. (2016) (Figure 1b and details in Supporting Information S1 (Tables 1 to 3)). First, criteria for five data quality indicators including reliability, completeness, spatial correlation, temporal correlation, and other (technological) correlation (Weidema & Wesnæs, 1996) are redeveloped by assigning scores from 0.5–5. Second, data sensitivity level  $a$  is considered and classified into “not sensitive,” “medium sensitive,” and “highly sensitive,” where:  $a_{\text{not sensitive}} = 0.325$ ;  $a_{\text{medium sensitive}} = 2 \cdot a_{\text{not sensitive}} = 0.65$ ;  $a_{\text{highly sensitive}} = 4 \cdot a_{\text{not sensitive}} = 1.3$ . Finally, the determined indicator scores and sensitivity levels are translated into uncertainties, that is, coefficients of variation (CV), via continuous exponential function (Hedbrant & Sörme, 2001) in Equation (1); where  $b = 1.105$ ,  $e = 2.71828$  (mathematic constant).

$$CV = a \cdot e^{b \cdot (\text{score} - 1)} \quad (1)$$

The overall uncertainty,  $CV_{\text{total}}$ , is calculated as follows:

$$CV_{\text{total}} = \sqrt{CV_{\text{reliability}}^2 + CV_{\text{completeness}}^2 + CV_{\text{geographical}}^2 + CV_{\text{temporal}}^2 + CV_{\text{technological}}^2} \quad (2)$$

The definition of data quality indicator scores and choice of sensitivity level  $a$  and  $b$  are based on specific data background context (cf., Weidema & Wesnæs, 1996; Hedbrant & Sörme, 2001; Zoboli, Laner, Zessner, & Rechberger, 2016; Laner et al., 2016). This uncertainty analysis framework is applied for both primary and secondary data. For household productions, only two indicators “reliability” and “completeness” are considered because measurements were implemented at the same production installations. Therefore, spatial-, temporal-, and technological correlations are similar and data uncertainty is estimated following Equations (3) and (4). Furthermore, in most cases of assumption, uncertainty is assigned only one score, often with “3.5.”

$$CV_{\text{goods}} = \sqrt{CV_{\text{reliability}}^2 + CV_{\text{completeness}}^2} \quad (3)$$

$$CV_{\text{substance}} = \sqrt{CV_{\text{reliability}}^2 + CV_{\text{completeness}}^2 + CV_{\text{goods (calculated)}}^2} \quad (4)$$

### 2.4.1 | Refined aspects of data uncertainty analysis

This study confronts numerous data limitations, notably data conflicts and data scarcity from varying material flow systems (e.g., household productions, regional systems). Including data uncertainty is the most suitable way to solve these constraints. The previous studies (see Section 1.2.2) mainly focused on secondary data and/or lacked systematic approaches for imperfect empirical data and strongly localized data. This limits MFA applicability, especially under unstable conditions of transition economies like Vietnam. This work improves the situation by defining criteria for assigning data indicator scores and sensitivity levels for both *primary and secondary data* in a comprehensive and consistent manner (see details and examples in Supporting Information S1 (Tables 1 to 3), S2 (Tables 4, 5), and S4.2 (Table 8)). Therefore, uncertain data aspects are covered as well as possible and transparently quantified.

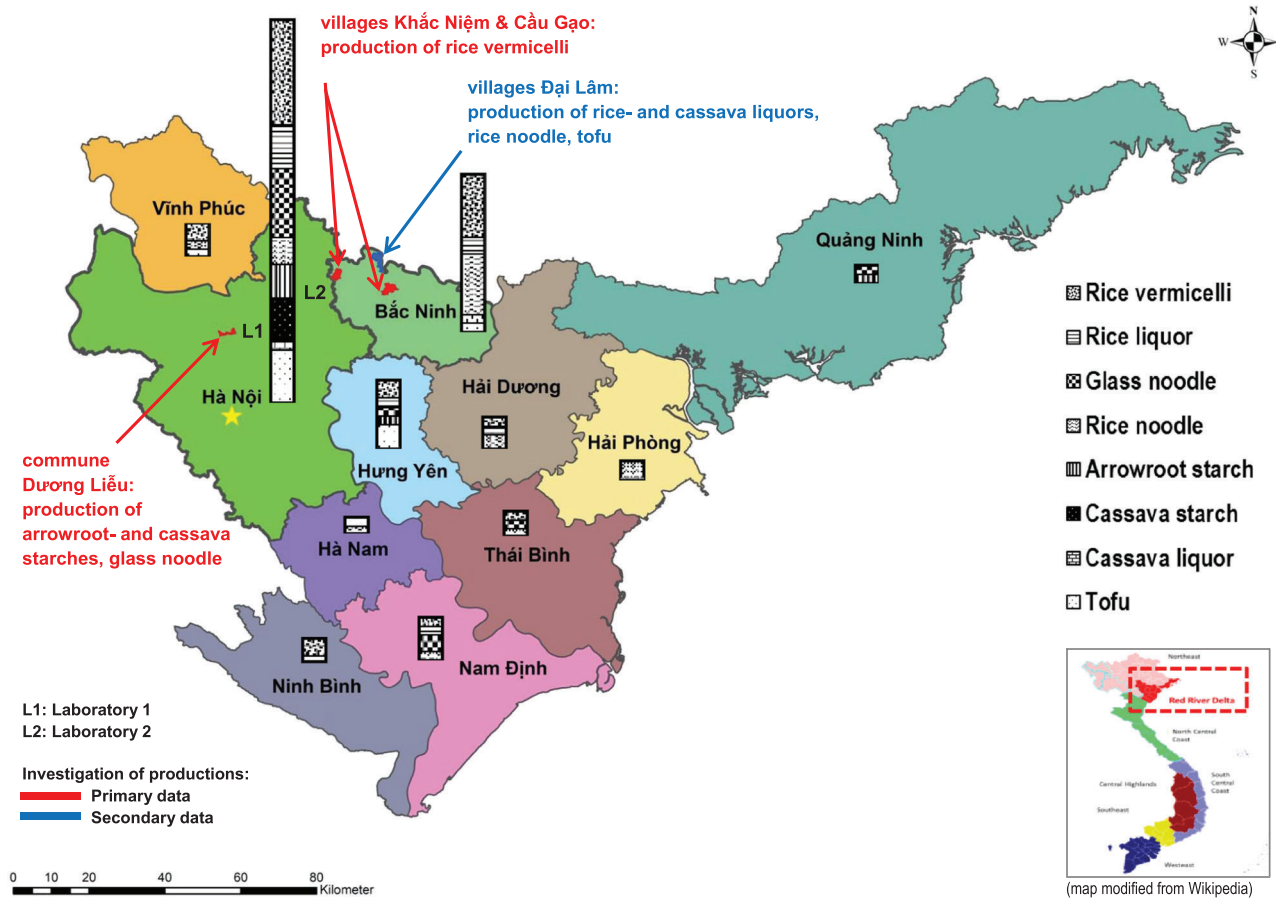
## 2.5 | Study area and data collection

### 2.5.1 | Study area

The RRD is located in the western coastal zone of the Gulf of Tonkin and consists of 11 Northern provinces in Vietnam (Figure 3). RRD represents a small area (6.4%) of 21,260 km<sup>2</sup> but is most densely populated, with 21 million inhabitants providing 23% of the total national population. About 64% of its residents lives in rural areas (GSO, 2017). The delta is formed by sediment from the Red River flowing from Southwest China through several Northern provinces of Vietnam. Favored by advantageous geography and natural resources, RRD is known for the second largest agricultural production zone and one of the most developed economic regions nationwide (Chi, 2005; Thách, 2006; Fanchette et al., 2010; WB, 2012; Sakata, 2013). It is also recognized for the highest rate of individual business establishments—the major driver for rural industrialization (Sakata, 2013). Nonetheless, RRD is an exemplary case suffering from serious environmental damage triggered by rapid industrialization and urbanization (WB, 2013; ADB, 2013, 2015).

Household productions in FPCVs belong to rural cottage industries. There are 86 FPCVs from ~130 food processing villages in RRD (own synthesis). However, in this study, information was only obtainable for 66 well-documented FPCVs, dominantly located in Hà Nội (40%) (Figure 3 and further details in Supporting Information S4.1 (Table 7)).





**FIGURE 3** The Red River Delta region (shapefiles modified from [www.gadm.org](http://www.gadm.org)), investigation sites, and distribution of agro-Food Processing Craft Villages

## 2.5.2 | Data collection

As much information is collected as possible to achieve the over-determination (more equations than unknown) and utilize functions of gross error detection and data reconciliation within software STAN (see examples in Supporting Information S3 (Figures 1 to 3, Table 6)). For productions of cassava starch (CS), arrowroot starch (AS), rice vermicelli (RV), and glass noodle (GN); two data collection campaigns were undertaken at the beginning of 2015 and 2016 (around traditional New Year), when productions are at peak. Measurements of household productions and sampling were conducted in well-known FPCVs in Hà Nội and Bắc Ninh. Sampling and sample preservation were performed according to instructions and methods described in Gy (1998). Analyses were conducted at laboratories of Hanoi University of Science, Vietnam National University (see Supporting Information S9 (Table 20) for analytical methods). For the remaining productions of rice noodle (TN), tofu (Tf), cassava liquor (CL), and rice liquor (RL); data were extracted from a recent study of Meier (2016) on a liquor processing village Đại Lâm (Bắc Ninh) (Figure 3). Data used for estimating regional production capacities were synthesized from *all available sources* and telephone interviews of the producers and local authorities in 2016 and 2017. For *relevant processes* of private *Households*, *Pig Farming*, and *Rice Cultivation*, data were compiled mainly from literature, statistics office, and own synthesis (see further details in Section 4.2 and Supporting Information S4.2 (Tables 8, 10), S8.2 (Figures 10 to 12; Tables 15a, 15b, 16a, 16b, 17a, 17b, 18) for actual data set and data sources).

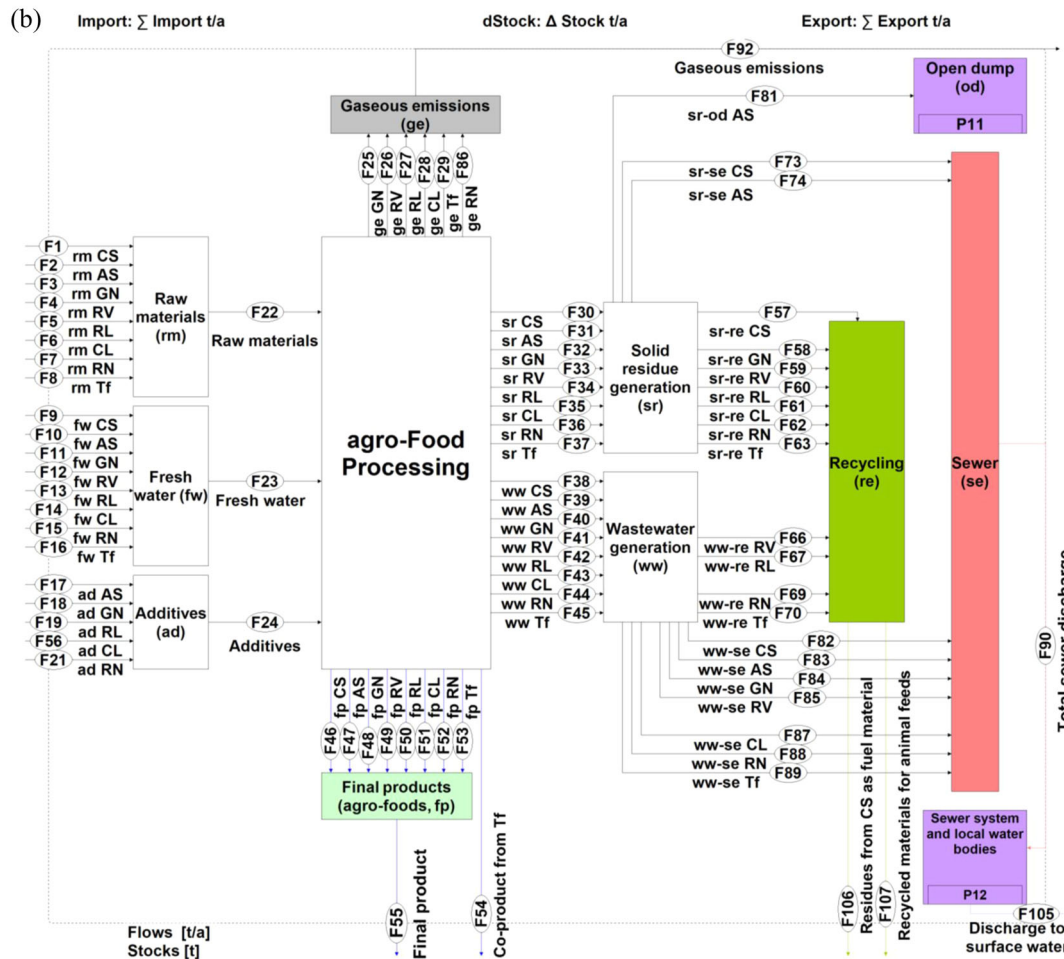
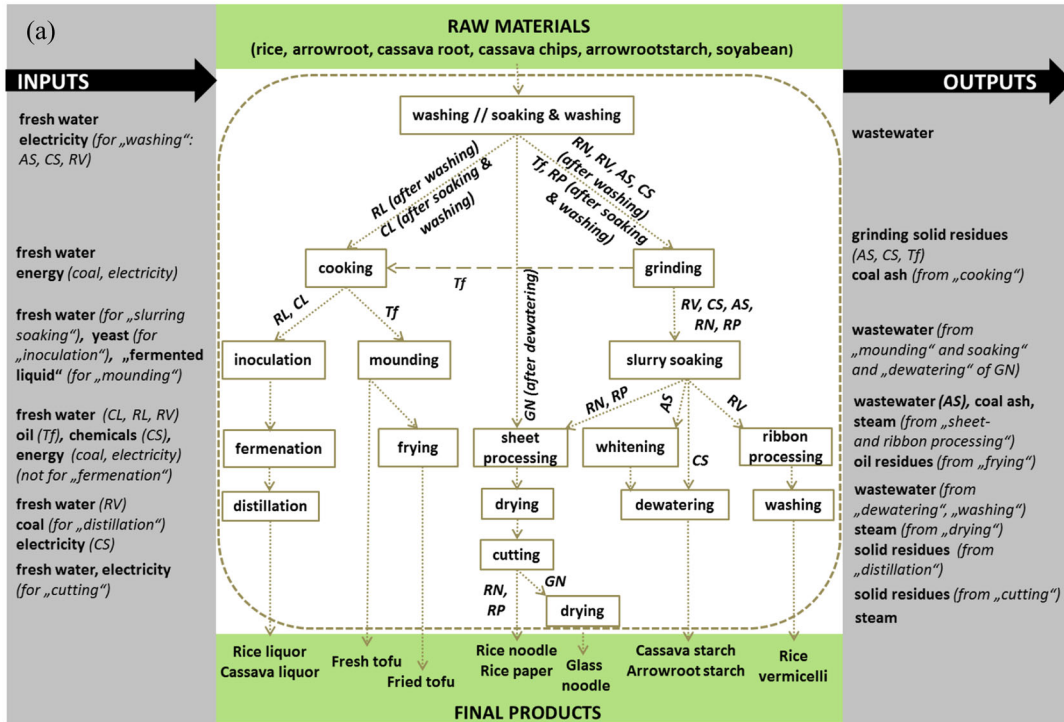
## 2.6 | Upscaling of agro-food processing from household to regional level

Eight household productions including detailed steps (Figure 4b) are modeled *individually* as a prerequisite for the upscaling (Figure 1c).

### 2.6.1 | Estimation of regional production capacities

First, the *existing number and types of FPCVs in RRD* are assessed. Second, production capacity (tons<sup>1</sup> of product/year) of each village  $i$  ( $PC_{\text{village},i}$ ) is estimated and cross-checked against information obtained from household productions (e.g., ratio between raw material to final product) and/or

<sup>1</sup> Tons refer to metric tons throughout this article.



**FIGURE 4** a) Generalized agro-food production steps (own survey), b) Modeling of agro-Food Processing in Red River Delta in 2015. Abbreviations: AS, Arrowroot Starch; CS, Cassava Starch; GN, Glass Noodle; RV, Rice Vermicelli; RL, Rice Liquor; CL, Cassava Liquor; RN, Rice Noodle; Tf, Tofu. rm, raw materials; fw, fresh water; ad, additives; ge, gaseous emissions; fp, final product; sr, solid residues; ww, wastewater; re, recycling; se, sewer; od, open dump; F, Flow; P, Process. The rectangle inside a process symbolizes stocks. Units: t, tons; a, annum. Tons refer to metric tons

literature. If data are scarce, they are assumed based on proxy data or experience values implied from production investigations (e.g., number of production establishments, peak and frequency of productions). Finally, values are aggregated to get the total regional production capacity for Goods ( $PC_{reg\_Goods}$ , Equation (5)) and substance ( $PC_{reg\_substance}$ , Equation (6)).

$$PC_{reg\_Goods} = \sum_{i=1}^n PC_{village, i} \quad (5)$$

$$PC_{reg\_substance} = C_{hh\_product} \cdot PC_{reg\_Goods} \quad (6)$$

where  $n$  is total number of FPCVs,  $C_{hh\_product}$  is substance concentration of final product from household production.

The uncertainty of regional production capacities is calculated by applying the Gaussian law for addition (Equation (7)) and multiplication (Equation (8)).

$$\sigma_Y = \sqrt{\sigma_{x_1}^2 + \sigma_{x_2}^2 + \dots + \sigma_{x_n}^2} \quad (7)$$

$$CV_Y = \sqrt{CV_{x_1}^2 + CV_{x_2}^2 + \dots + CV_{x_n}^2} \quad (8)$$

where  $Y$  is function of variable  $x$ ,  $\sigma$  is standard deviation,  $CV$  is coefficient of variation ( $CV = \frac{\sigma}{\bar{x}} \cdot 100$ ,  $\bar{x}$  is mean value).

## 2.6.2 | Calculation of transfer coefficients

From the modeled household production, the transfer coefficient at household level of each flow  $f$  ( $TC_{hh}^f$ , Equation (9)) is defined as the ratio between its flow mass ( $\dot{m}_{hh}^f$ , in kg/day) and the final product ( $PC_{hh}$ , in kg/day) and its uncertainty is calculated following Equation (8).

$$TC_{hh}^f = \frac{\dot{m}_{hh}^f}{PC_{hh}} \quad (9)$$

## 2.6.3 | Modeling of regional productions

The regional productions are established based on systems defined for household productions applying similar transfer coefficients ( $TC_{hh}^f$ ). Together with the regional production capacity ( $PC_{reg}$ ), the mass of flow  $f$  is extrapolated to regional level ( $\dot{m}_{reg}^f$ , in tons/year, Equation (10)). Entering regional flow values into STAN, the regional productions are subsequently modeled.

$$\dot{m}_{reg}^f = PC_{reg} \cdot TC_{hh}^f \quad (10)$$

See Supporting Information S4.2 (Table 8) and S6 (Tables 1, 2; Figures 14, 15) for the demonstration of this upscaling concept.

## 2.6.4 | Modeling of total regional agro-food processing

It is unnecessarily complicated to include all detailed production steps (Figure 4a) in one model. Instead, the *agro-Food Processing (FP)* is simulated using major flows from eight modeled regional productions (Figure 4b) to provide a better overview of material flow system.

Flow and stock values are given in Supporting Information S7.1 (Tables 14a, 14b), the following presents mathematical relationships of *agro-Food Processing*:

$$\sum \dot{m}_{i,FP} = \sum \dot{m}_{e,FP} + \sum \dot{m}_{dS,FP} \quad (11)$$

where  $\dot{m}_{i,FP}$ ,  $\dot{m}_{e,FP}$ ,  $\dot{m}_{dS,FP}$  are import ( $i$ ), export ( $e$ ), and delta stock ( $dS$ ).

The import (Equation (12)) includes raw materials ( $rm$ , Equation (13)), fresh water ( $fw$ , Equation (14)), and additives ( $ad$ , Equation (15)) from eight productions (1 = CS, 2 = AS, 3 = GN, 4 = RV, 5 = RN, 6 = Tf, 7 = CL, 8 = RL).

$$\dot{m}_{i,FP} = \dot{m}_{rm} + \dot{m}_{fw} + \dot{m}_{ad} \quad (12)$$

where

$$\dot{m}_{rm} = \sum_{k=1}^8 \dot{m}_{rm,k} \quad (13)$$

$$\dot{m}_{fw} = \sum_{k=1}^8 \dot{m}_{fw,k} \quad (14)$$



$$\dot{m}_{ad} = \sum_{k=1}^8 \dot{m}_{ad,k} \quad (15)$$

where  $k$  indicates production type.

The delta stock (Equation (16)) is calculated as stocks in open dump (OD, where solid residue from AS ( $od\_AS$ ) is disposed of, Equation (17)) and sewer system ( $se$ ) and local water bodies (SS&LWB, where wastewater ( $ww$ ) and solid residues ( $sr$ ) are discharged into, Equation (18)).

$$\dot{m}_{dS,FP} = \dot{m}_{FP,OD} + \dot{m}_{FP,SS\&LWB} \quad (16)$$

where

$$\dot{m}_{FP,OD} = \dot{m}_{od\_AS} \quad (17)$$

$$\dot{m}_{FP,SS\&LWB} = \sum_{k=1}^7 \dot{m}_{ww-se,k} + \sum_{k=1}^2 \dot{m}_{sr-se,k} \quad (18)$$

The export (Equation (19)) includes final product ( $fp$ , Equation (20)), coproduct as soyamilk ( $sm$ ) from  $Tf$ , recycled ( $re$ ) solid residues as fuel material ( $fm$ ) from CS, recycled materials for animal feeds ( $af$ , Equation (21)), discharge to surface water ( $dsw$ ), and gaseous emissions ( $ge$ , Equation (22)).

$$\dot{m}_{e,FP} = \dot{m}_{fp} + \dot{m}_{sm-Tf} + \dot{m}_{re,fm-CS} + \dot{m}_{re,af} + \dot{m}_{dsw} + \dot{m}_{ge} \quad (19)$$

where

$$\dot{m}_{fp} = \sum_{k=1}^8 \dot{m}_k \quad (20)$$

$$\dot{m}_{re,af} = \sum_{k=3}^8 \dot{m}_{sr-re,k} + \sum_{k=4}^6 \dot{m}_{ww-re,k} + \dot{m}_{sr-re,af-CS} + \dot{m}_{ww-re,RL} \quad (21)$$

$$\dot{m}_{ge} = \sum_{k=3}^8 \dot{m}_{ge,k} \quad (22)$$

### 3 | RESULTS

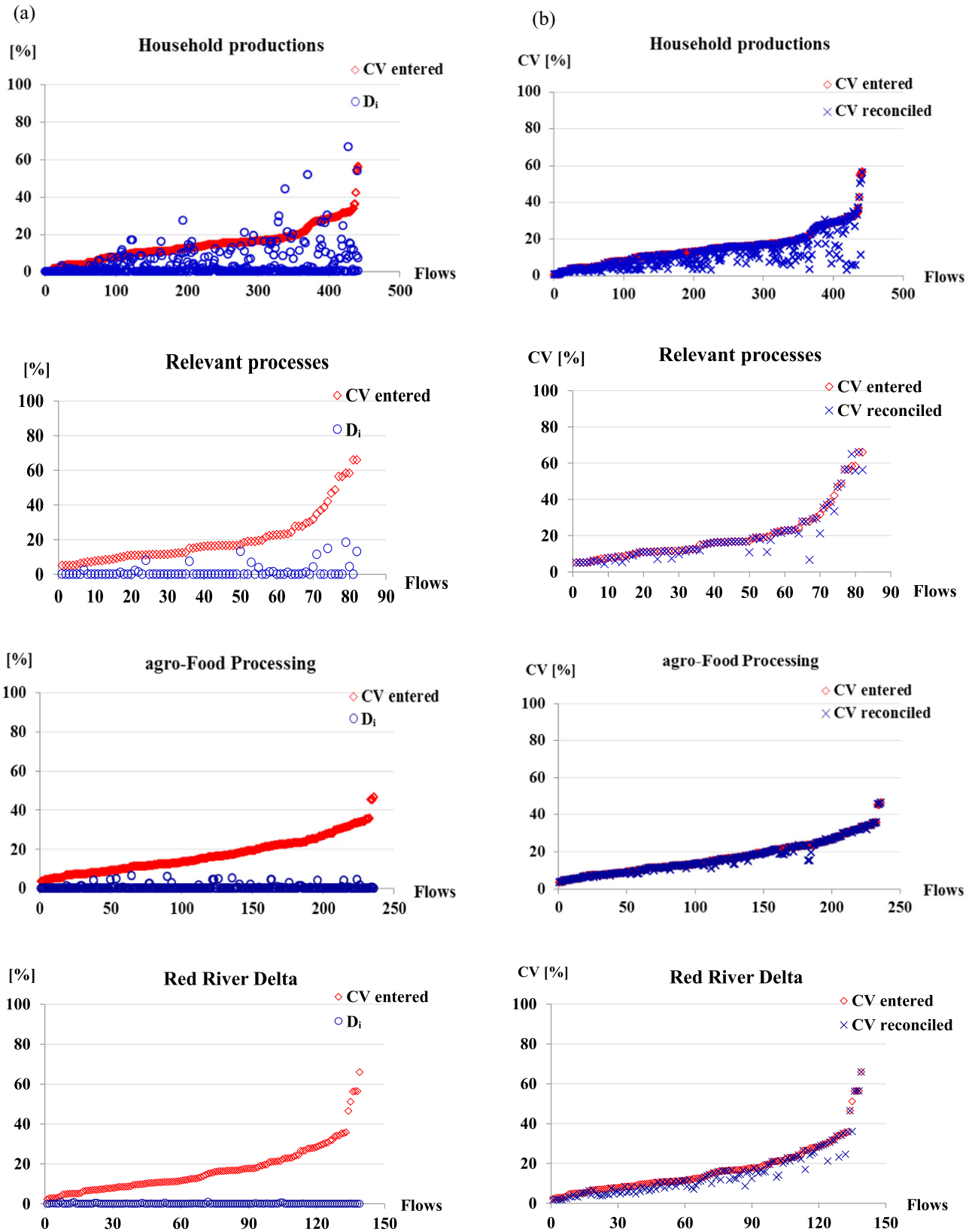
The following processes are categorized: household productions including productions using primary data (AS, CS, GN, RV) and productions using secondary data (RN, Tf, RL, CS), relevant processes (*Households, Pig Farming, Rice Cultivation, agro-Food Processing, and Red River Delta*).

Figure 5 presents results implied from the application of data uncertainties characterization, further details are found in Supporting Information S10 (Tables 21a to 21e). Figure 5a illustrates the mean value change after reconciliation ( $D_i$ ) and compares it with entered uncertainties, indicating flows in which  $D_i$  is higher than entered CV are insignificant. Figure 5b compares the entered and reconciled uncertainties, showing uncertainty reduction after reconciliation.

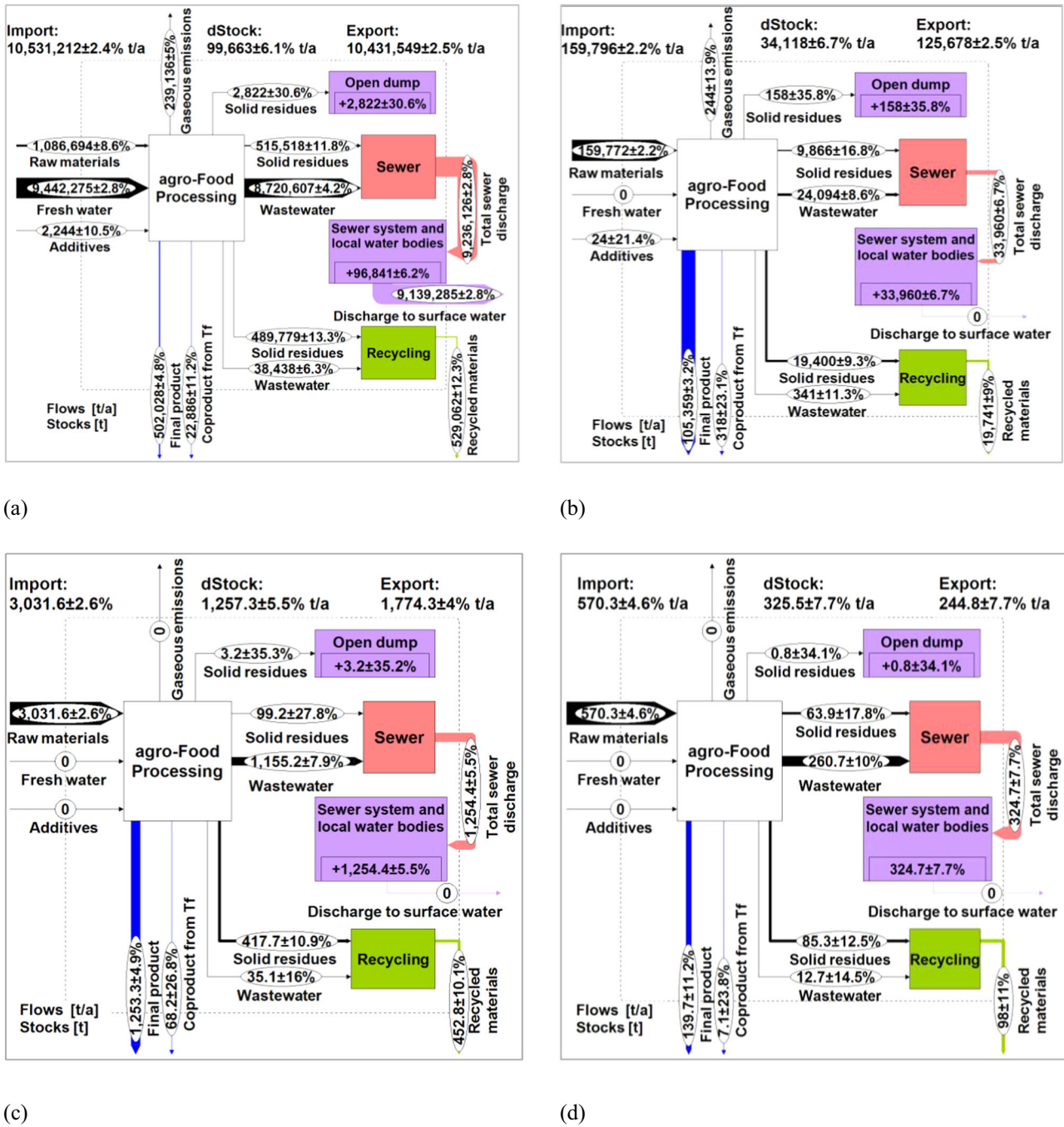
Figure 6 describes simplified models of *agro-Food Processing* (see Supporting Information S7.2 (Figures 6 to 9) for detailed models).

In total,  $502,025 \pm 4.8\%$  tons/year of agro-foods (fresh mass basis) were produced from FPCVs in RRD in 2015, mainly provided (88%) by CS (29%), RV (26%), GN (19%), and RN (14%). Most material consumption (89%) attributes to AS (42%), CS (35%), and GN (12%). Across productions, the ratio of raw material to final product varies from 0.5–6.7; highest for AS (6.7), CS (2.4), GN (1.7); followed by CL (1.1), RN (1), and RL (1); and lowest for Tf (0.5) and RV (0.5).

Table 1 quantifies the material metabolism in *Red River Delta* (see Supporting Information S8.2 [Table 19] and S8.3 [Figures 13 to 16] for detailed models), indicating an uneven material distribution between *agro-Food Processing* and relevant processes.



**FIGURE 5** a) Entered uncertainties and mean value adjustment ( $D_i$ ), b) Entered uncertainties and reconciled uncertainties. CV, Coefficient of Variation



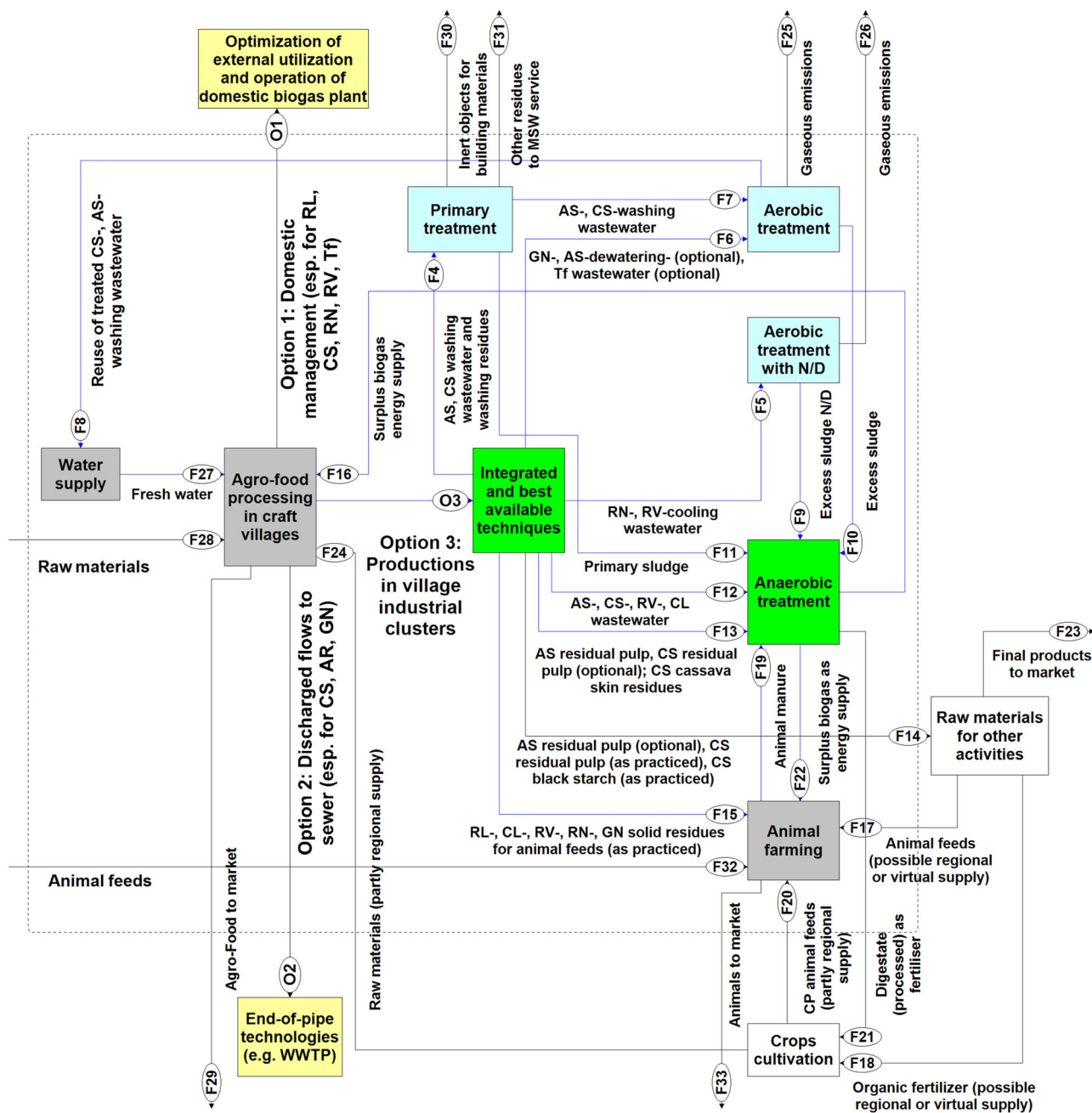
**FIGURE 6** Simplified models of *agro-Food Processing* in Red River Delta in 2015: a) balance of Goods, b) balance of organic carbon, c) balance of nitrogen, d) balance of phosphorus. Data are extracted from detailed models. The rectangle inside a process symbolizes stocks. Tf, Tofu production; Units: t, ton; a, annum. Tons refer to metric tons

## 4 | DISCUSSION

### 4.1 | Implication of data uncertainty analysis

#### 4.1.1 | Overcoming specific data limitations

Two notable data limitations have been solved as follows. For productions using *primary data*, data are relatively inconsistent due to production unprofessionalism and imperfect measurements. Accordingly, detailed criteria were constructed for diverse data sources, sampling quality, measurement frequency, analysis parameters, and processing characteristics, etc. This facilitated gross error elimination and reconciled conflicting data, particularly for highly unstable productions of AS, GN, and RV. For estimating regional production capacities, data are substantially scarce



**FIGURE 7** Selective options of material management for agro-food processing craft villages in Red River Delta. Abbreviations: AS, Arrowroot Starch; CS, Cassava Starch; GN, Glass Noodle; RV, Rice Vermicelli; RL, Rice Liquor; CL, Cassava Liquor; RN, Rice Noodle; Tf, Tofu; N/D, Nitrification/Denitrification; WWTP, Waste Water Treatment Plant; F, Flow; O, Option; esp., especially. The dashed line rectangle symbolizes the boundary of a village production cluster

and uncertain. Correspondingly, criteria are exclusively designed for data compiled from informal sources (i.e., public websites), interviews, various levels of studies and reports, and assumptions. Based on this, material flow systems were transparently modeled and upscaled using the best possible data availability. For more details, see examples in Supporting Information S2 (Tables 4, 5), S3 (Figures 1 to 3, Table 6), S4.2 (Tables 8 to 10), and S6 (Tables 12, 13; Figures 4, 5).

#### 4.1.2 | Data consistency

Data consistency is quantified by the percentage (%) difference of entered and reconciled mean values,  $D_i$ . The lower the  $D_i$  is, the more consistent the input data are. Unreasonable uncertainty characterization and/or more redundant data can increase possibilities of balance constraints (Klinglmaier et al., 2016). Across processes,  $D_i$  varies from 0–4.8% (Figure 5a) and is in line with values of Data Reconciliation Quality (Cencic, 2016a) calculated by STAN. With the lowest  $D_i$ , data are most consistent for *Red River Delta* (0.07%), and *agro-Food Processing* (0.45%), followed by *relevant*

**TABLE 1** Material shares and exchanges among *agro-Food Processing* (FP), *Rice Cultivation* (RC), *Pig Farming* (PF), and *Households* (HH) in *Red River Delta*. dStock, delta Stock, org.C, organic carbon, N, nitrogen, P, phosphorus. % is percentage of import (by weight). The arrow illustrates material exchanges between processes within system boundary. Data are extracted from detailed models of *Red River Delta*

Import		RC	PF	HH	FP	dStock	Material exchanges
Materials	[tons/year]	[%]	[%]	[%]	[%]	[%]	[%]
Goods	27,428,922,238 ± 6.1%	98.2	0.13	1.65	0.038	15.6	FP→PF: $1.93 \cdot 10^{-3}$ HH→PF: $1.8 \cdot 10^{-4}$ HH+PF→RC: $3.35 \cdot 10^{-2}$
org.C	8,082,689 ± 2.7%	72.5	15.6	9.92	1.98	6.3	FP→PF: $2.4 \cdot 10^{-1}$ HH→PF: $3.3 \cdot 10^{-2}$ HH+PF→RC: 1.28
N	389,346 ± 6.6%	52.7	31.8	14.7	0.78	37	FP→PF: $1.15 \cdot 10^{-1}$ HH→PF: $2.74 \cdot 10^{-2}$ HH+PF→RC: 4.38
P	90,755 ± 6.8%	41.5	46.8	11.1	0.63	60	FP→PF: $1.07 \cdot 10^{-1}$ HH→PF: $1.83 \cdot 10^{-2}$ HH+PF→RC: 4.35

[After initial online publication, the FP→PF values for rows N and P were corrected.]

processes (1.5%). By contrast, data are least consistent for household productions (3.6%) including productions using secondary data (1.7%) and productions using primary data (4.8%)—remarkably for GN, AS, and RV where *gross errors* were detected. With differing  $D_i$  from 0.75–3.3%, data are generally more consistent for Goods than substances.

#### 4.1.3 | Uncertainty assessment

##### Input uncertainty range

Overall, the uncertainty ranges from 0.26% to 66% (Figure 5b). Nearly half of flows have CVs of 10–20%, which are considered moderate uncertainties (cf., Crowe, 1996; Weidema & Wesnæs, 1996; Hedbrant & Sörme, 2001; Laner et al., 2016; Brunner & Rechberger, 2016), followed by levels 0–10% (27% of flows) and 20–30% (17%). The CVs > 30% are minor (9%). The lowest range of 0–5% pertains to household productions, *agro-Food Processing*, and *Red River Delta*. The highest CV range of 60–70% belongs to relevant processes (remarkably for *Rice Cultivation*) and *Red River Delta*. Productions using primary data have substantially higher uncertainties (max. 56%, notably for GN and RV) than productions using secondary data (max. 29%). The rates of larger uncertain flows (CVs > 20%) in Goods (14%) and org.C (19%) are considerably lower than N (41%) and P (42%). Uncertainties estimated for regional production capacities range from 8–22%, with the highest for CL (22%) and the lowest for RN (8%) (see Supporting Information S4.2 (Tables 8, 9)).

##### Uncertainty adjustment

The percentage change of uncertainty before and after reconciliation is defined as uncertainty adjustment,  $CV_i$ . Reconciled uncertainties are generally lower than entered ones, except for highly uncertain flows (cf., Klinglmair et al., 2016; Laner et al., 2016). Overall, the average  $CV_i$  is 13%, varying from 2.7–19% (Figure 5b). Household productions have the greatest  $CV_i$  (19%). Particularly, productions using primary data have larger change (23%, dominantly for GN (31%)) than productions using secondary data (14%). *Red River Delta* has the second highest  $CV_i$  (15.5%), followed by relevant processes (7%, notably for *Rice Cultivation* (12%)). The smallest  $CV_i$  belongs to *agro-Food Processing* (2.7%). The uncertainty adjustments are almost comparable for Goods (14%), P (13.6%), and N (12%), which are relatively higher than org.C (9%).

##### Confidence of uncertainty estimation

The distance of  $D_i$  from entered CV indicates whether the uncertainty estimation is overly optimistic ( $D_i > CV$ ) or pessimistic ( $D_i < CV$ ) (cf., Klinglmair et al., 2016). Overall, flows with overly optimistic uncertainties are insignificant (2.6%) (Figure 5a). This occurs to household productions (5% of flows)—noticeably for GN (12%), RV (6%), CL (6%), and AS (5%). Goods (0.6%) and P (1.7%) have lower proportions of overly optimistic uncertainties than org.C (4%) and N (5%).

In summary, the data uncertainty quality and data consistency quantitatively reflect data characteristics (e.g., sources, availability, application of reconciled flows like in *agro-Food Processing*, *Red River Delta*) and process specificity.



## 4.2 | Material flow behaviors of agro-food processing

The following analyzes material flow behaviors of *agro-Food Processing*. Otherwise stated, material share is expressed as percentage (%) of the import.

### 4.2.1 | Balance of goods

Fresh water represents the greatest part (89.7% by weight or  $9,442,275 \pm 2.8\%$  tons/year). Raw materials account for about 10.3% ( $1,086,694 \pm 8.6\%$  tons/year) and the amount of additives is insignificant ( $0.02\%$  or  $2,244 \pm 10.5\%$  tons/year). Of the output flows, the majority (87.7%) is discharged without treatment into the sewer. Both final product and recycled materials have comparable shares of about 5%. The rest remains in co-product (0.2%, from Tf), is deposited in open dumps (0.03%, from AS residues), and released as gases into the atmosphere (2.2%). Solid residues amount to 9.6%: half of this (4.7%) is utilized mainly for animal feeds; another fraction (4.9%) is disposed of into the sewer. Contrarily, wastewater accounts for a much larger proportion (83.2%) and is almost completely released into the sewer (82.8%); only a minor fraction (0.4%) is recycled for animal feeds. *The majority of Goods is discharged directly into the sewer significantly contributed by wastewater, indicating not only a huge waste of water resource but also a burden for obsolete village sewer systems. Utilized materials account for a small part (~5%) mainly contributed by solid residues. Stocks provide a negligible share (1%).*

### 4.2.2 | Balance of org.C

The largest percentage (66% by weight of  $159,796 \pm 2.2\%$  tons/year) stays in final product. Another considerable share (21%) is deposited in the sewer. The recycled materials account for 12.4%. Small fractions are distributed in by-product (0.2%), gases (0.15%), and open dumps (0.1%). About 18.4% stays in solid residues: nearly two-thirds of this is recycled (12%); the rest is discharged into the sewer (6%) and accumulated in open dumps (0.1%). Wastewater contributes 15.3%. Unlike solid residues, most of the org.C in wastewater (15.1%) is disposed of into the sewer and a negligible proportion (0.2%) is utilized for animal feeds. *Compared to Goods (1%), a significantly higher fraction of org.C (21%) becomes stocks; about 70% of this originates from wastewater. The amount recycled (12%) is still smaller than stocks. The majority (66%) remains in final product.*

### 4.2.3 | Balance of N

Different from org.C, a smaller share (40.7% by weight) of  $3,032 \pm 2.6\%$  tons/year of import N is transformed into final product. Likewise, an equivalent proportion (41.5%) is discharged into the sewer. With 14.9%, recycled materials account for a lower contribution. The minor parts remain in by-product (2.2%) and open dumps (0.1%). The amount in wastewater (39.5%) is nearly double that found in solid residues (17%). As for org.C, most of the N in wastewater becomes stocks in the sewer (38%) and an insignificant part is used for animal feeds (1%). In contrast, three-quarters of N in solid residues (13.7%) is recycled; the rest is disposed of into the sewer (3%) and open dumps (0.1%). *Compared to org.C, the percentage of N discharged into the sewer is higher by a factor of two but the amount recycled is nearly comparable. Stocks account for a significant fraction (41.7%) majorly contributed by wastewater. The recycled (14.9%) is mainly provided by solid residues and relatively smaller than stocks.*

### 4.2.4 | Balance of P

About 57% (by weight) of  $570.4 \pm 4.7\%$  tons/year of import P is disposed of into the sewer. Approximately a quarter (24.6%) remains in final product and a smaller portion (17%) is recycled. The rest is deposited in open dumps (0.14%) and remains in by-product (1.3%). In the output flows, the greatest contribution (48%) comes from wastewater, which is majorly discharged into the sewer (45.7%). Solid residues account for 26%: over half of this is recycled (14.7%), other smaller parts are discarded into the sewer (11%) and open dumps (0.01%). *Unlike org.C and N, the majority of P (57%) is discharged without treatment and accumulated as stocks mainly in the sewer; the recycled (17%) is slightly higher but still much smaller compared to stocks.*

### 4.2.5 | Total sewer discharge

The above analyses show that most materials are discharged untreated into the sewer. Consequently, sewer systems and local water bodies become active biological reactors fueled by substance stocks whose concentrations vastly exceed natural resilience capacities. In particular, the overall concentrations exceed regulated values (QCVN 40:2011/BTNMT, 2011) by a factor of 78 for COD, 3.4 for N, and 5.8 for P, leading to stinky smell in local sewers and over-nutrition of the surrounding soil and water. The concentrations are seriously high for RV, CS, and CL; while the loads are mainly contributed by CS, AS, and RV accounting for 87% (by weight) of Goods, 98% of org.C, 99% of N, and 97% of P of the total sewer discharge. *These findings suggest that specific priorities should be given to critical flows and productions for environmental and resource management in FPCVs.*

## 4.3 | Comparison of agro-food processing with relevant processes

Table 1 shows *agro-Food Processing* represents the least and negligible import shares in *Red River Delta*; whereas *Rice Cultivation* is responsible for the highest proportions (except P), followed by *Pig Farming* and *Households* (for more details see Supporting Information S8.3 (Figures 13 to 16)).

N and P have much higher stock rates than Goods and org.C. Unlike *Rice Cultivation*, *agro-Food Processing* is an insignificant contributor to stocks. Material exchanges among *agro-Food Processing* and *relevant processes* are relatively modest (<5% of import, by weight). In particular, residual materials from *agro-Food Processing* utilized for pig feeds provide minor shares corresponding to 14% of Goods, 1.5% of org.C, 0.36% of N, and 0.23% of P in commercial feeds required for *Pig Farming*. Compared to commercial (chemical) fertilizer required for *Rice Cultivation*, human and pig excreta utilized for fertilizer are significantly higher by a factor of 13.7; however, they make up trivial shares equal to 1.8% of org.C, 8.9% of N, and 10.5% of P. Although *agro-Food Processing* has the least material shares in *Red River Delta*, the pollution in FPCVs is still severe at the local level due to the home-based location of productions. This contamination is highly loaded because it is generally contributed by the manure mismanagement from accompanying activity of *Pig Farming*. The material flow behaviors of *agro-Food Processing* and *relevant processes* in *Red River Delta* indicate inefficient management of regional sanitation system. *Optimizing material exchanges among them suggests a solution to environmental problems in FPCVs.*

## 4.4 | Recommendations of material flow management

### 4.4.1 | General principle

The above quantified material flow behaviors imply open material cycles causing resource losses and environmental damage in FPCVs. Preventing these by applying industrial ecology concept to close material loops at various system levels (Lifset & Graedel, 2002; Ehrenfeld & Chertow, 2002; Graedel & Lifset, 2016; Chertow & Park, 2016) is recommended. Measures should be production specific focusing on critical productions and flows and production establishment level because of material utilization flexibility for producers (Ehrenfeld & Chertow, 2002). If infeasible, end-of-pipe technologies can be a complement or alternative; in which anaerobic treatment should be prioritized over aerobic treatment due to high organic content and energy and resource recovery potentials of the discharge (Rosenwinkel & Nagy, 2000; EIPPCB, 2006; Meier, 2016; JRC, 2017). In this regard, Figure 7 summarizes three possible options of material flow management (see Supporting Information S11 (Table 22) for more details).

### 4.4.2 | Option 1: Optimization of domestic material management

This option is suitable for the current situation of FPCVs while adapting or waiting for better environmental planning and regulations. Here, residual material utilization within production processes or with external activities (e.g., animal raising) is promoted. Unused production residues and animal manure can be treated in domestic biogas plants with cautious management of bio-slurry (e.g., Chi, 2003; De Groot & Bogdanski, 2013).

### 4.4.3 | Option 2: Communal wastewater treatment plant

This alternative can be combined with option 1 and applied to all production types when wastewater treatment plants are installed in FPCVs (e.g., Meier, 2016; Hai et al., 2016). However, caution should be given to the huge quantity of solid residues generated from CS and AS. This measure can also be implemented when productions with controlled capacities and low environmental pollution level are allowed to remain in residential areas and polluting productions are relocated in village production clusters as stated in Decision 577/QĐ-TTg (2013) and Circular 31/2016/TT-BTNMT (2016).

### 4.4.4 | Option 3: Industrial symbiosis for village production clusters

This is the most desired option when the government is successful in relocating all productions to village production clusters. Here, materials are exchanged within production processes and collocated activities in production clusters (e.g., animal farming, other productions, waste treatment facilities) or the proximity (e.g., crop cultivation, horticulture, municipal) (cf., Ehrenfeld & Chertow, 2002). However, this concept may require coordination from local authorities (e.g., Wang, Deutz, & Chen, 2017).

## 5 | CONCLUSION

From a total of  $10,531,212 \pm 2.4\%$  tons of materials (corresponding to  $159,775 \pm 2.2\%$  tons of org.C,  $3,032 \pm 2.6\%$  tons of N, and  $570.4 \pm 4.7\%$  tons of P) used for *agro-Food Processing* in RRD in 2015, only minor shares (about 5%, by weight) are transformed into final products and recycled, the majority (90%) is directly discharged mainly into the sewer (87.7%) as wastewater (82.8%) or emitted as waste gases (2.2%). The discharge becomes stocks equal to 1% of Goods, 21% of org.C, 42% of TN, and 57% of P. This unsustainable practice indicates open material loops implying huge material losses and consequently environmental damage in FPCVs. Although *agro-Food Processing* represents negligible material shares compared to *relevant activities* in *Red River Delta*, the FPCVs pollution is localized and alarming due to the home-based production sites and manure mismanagement from the coexisting *Pig Farming*. Avoiding these problems by circulating materials is contextually recommended for production establishments, from the current situation to the most desired scenario of village production clusters. Applying the refined data uncertainty analysis has solved specific data limitations, leading to fruitful balancing of material flow systems and upscaling of production processes from household to regional level. The results provide a transparent and reliable database supporting particular agro-food producers, relevant decision makers to

optimize production processes and handle environmental and resource issues in FPCVs, and a tangible framework for MFA community. Further studies can quantitatively assess the recommended material flow management options, focus on dynamic MFAs for long-term environmental planning, and master the applicability of data uncertainty analysis in the developing country context.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest

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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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