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ASSESSING THE PRODUCTIVITY, ECONOMIC AND SUSTAINABILITY IMPACTS OF *SHELL* DNA TESTING IN INDONESIAN OIL PALM SMALLHOLDINGS IN MUSI BANYUASIN AND PELALAWAN REGENCIES

ISMAIL MASKROMO[1]; JEANETTE KUMAUNANG[1]; KRISTIANTO NUGROHO[1]; A MUIS HASIBUAN[2]; RERENSTRADIKA TIZAR TERRYANA[3]; SYAFARUDDIN[4]; ENGELBERT MANAROINSONG[4]; MUHAMMAD A BUDIMAN[5]; ABDUL R PURBA[5]; NATHAN D LAKEY[6]; JARED M ORDWAY[6] and PUJI LESTARI[1]*

ABSTRACT

To assess the potential industrial vegetable oil (IVO) increase made possible by SHELL *DNA supply chain testing, we conducted a field survey to quantify the presence of low-yielding contaminant oil palms in smallholder plantations. In the survey, 9341 palms in 81 smallholdings in Musi Banyuasin (representing 88.8% of the total planted area) and 74 smallholdings in Pelalawan (representing 85.5% of the total planted area) were sampled and tested (planting year 2001 to 2020). Musi Banyuasin and Pelalawan regencies contained only 26.2% or 27.4% legitimate high-yielding hybrid* tenera *palms, respectively. The remaining 73.8% and 72.6% of palms were one of four undesirable low-yielding contaminant types. We determined that if* SHELL *DNA testing had been conducted in the past, smallholder FFB production* (i.e., *smallholder income) would have increased by 31.0% and 28.0%, PKO production would have increased by 31.0% and 28.0%, and CPO production would have increased by 49.0% and 46.0% in Musi Banyuasin and Pelalawan, respectively. We demonstrate that a 'screen-then-plant' paradigm for oil palm cultivation in Indonesia has the potential to improve the income of millions of Indonesian smallholders, increase the productivity of CPO and PKO mills, provide significantly increased feedstocks for biofuel conversion and further enhance the sustainability of the Indonesian palm oil industry.*

Keywords: non-*tenera* contamination, oil yield, *SHELL* gene.

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[1] Research Center for Horticultural and Estate Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor Km 46, Cibinong 16911, West Java, Indonesia.

[2] Research Center for Behavioral and Circular Economics, Research Organization for Governance, Economy, and Public Welfare, National Research and Innovation Agency. Jl. Jend. Gatot Subroto No. 10, Jakarta 12710, Indonesia.

[3] Research Center for Genetic Engineering, Research Organization for Life Sciences and Environment, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor Km 46, Cibinong 16911, West Java, Indonesia.

[4] Indonesian Agency for Agricultural Instruments Standardization, The Ministry of Agriculture, Jl. Raya Ragunan No. 29, South Jakarta, Jakarta 12540, Indonesia.

[5] PT Orion Biosains, Menara 165, 4th Floor, Diamond H Office, Jl. TB Simatupang Kav.1 Cilandak, South Jakarta, Jakarta 12560, Indonesia.

[6] Orion Genomics LLC, 3730 Foundry Way, Suite 218, St. Louis, MO 63110, USA

* *Corresponding author e-mail: puji016@brin.go.id*

INTRODUCTION

Indonesia has become the main driver for increasing vegetable oil usage for renewable biofuel production. At present, a small fraction of national transportation fuel is renewable under a Biodiesel B30 program which blends 30% of palm oil-based fuel into petroleum-based diesel fuel, primarily produced by large palm oil producers who supply first generation biofuel conversion plants with vegetable oil produced in their vertically integrated plantations and mills. Today, even though smallholders manage 41.2% of oil palm planted area nationally, smallholder production suffers from the cultivation of low-yielding palm types, little oil produced by smallholders is used as a green biofuel feedstock. Furthermore, smallholders have long been associated with deforestation through continuous expansion.

The government of Indonesia established the Smallholder Plantation Scheme (PIR) at the beginning of the 1980s to improve the economic welfare of smallholders. The scheme is of critical importance as smallholders have been, by far, the fastest increasing segment of the oil palm planted area even though large plantations were the cornerstone of early industry expansion. Increasing smallholder yield is an important strategy for enhancing smallholder welfare. While comprising less than 1% of the total input costs borne by smallholders, the purchase of high-purity oil palm seeds and seedlings remains the most important cost component of the replanting program, and to a great extent, the purity of the planting material determines fresh fruit bunch (FFB) yield over the life of the plantation. FFB yield and quality, in turn, determine smallholders' income as they sell fruit to supply chain intermediaries or directly to independent oil mills. To ensure that the oil palm industry, especially oil palm smallholders, benefit from high purity seeds, in 2015 the Government of Indonesia established the national standard for oil palm seeds (SNI 8211:2015) requiring that germinated seeds and the resulting nursery seedlings are the product of commercial DxP crosses by registered seed sources and that they have at least a 98% *tenera* purity. However, prior to the discovery of the *SHELL* gene (Singh *et al*., 2013), collecting accurate measurements of *tenera* purity on seed, nursery seedlings and production palms in plantations has been difficult, if not impossible, to obtain.

Recently, breakthrough technologies provided a path for Indonesia to power vehicles with green biofuels based on the conversion of smallholder-produced industrial vegetable oil (IVO). First, *SHELL* DNA testing technology (hereafter referred to as "*SHELL* testing") has demonstrated the ability to identify low-yielding palms, enabling their removal from the smallholder seedling supply chain prior to field planting (Ooi *et al*., 2023; Singh *et al.,* 2022; 2013). With a test-then-plant paradigm, *SHELL* testing can protect the smallholder seed and seedling supply chain, while enabling the exclusive cultivation of elite planting material nationally. *SHELL* testing promises to dramatically increase smallholder production while simultaneously driving the sustainable supply of biofuel feedstock originating from the smallholder sector. Second, a next-generation biofuel conversion technology, developed in Indonesia, has demonstrated an alternative conversion of IVO to green biofuel in small-scale conversion mills, enabling the construction of small next-generation mills throughout the country adjacent to smallholder cooperatives which can supply the mills with higher quantity and quality fruit. Combined, these advances will forge a renewable green fuel future for Indonesia while benefitting smallholders.

The National Research and Innovation Agency (BRIN) through the National Strategic Project (PSN) has entered the pilot feasibility stage through the construction of two green biofuel conversion mills in Musi Banyuasin and Pelalawan regencies. The National Research and Innovation Agency through the National Research Project (PRN) funded the Estate Crop Research Center under the former Indonesian Agency for Agricultural Research and Development (IAARD) to achieve the following aims: Validate the accuracy of *SHELL* testing, conduct a contamination survey with *SHELL* testing to quantify the productivity of smallholdings in the two regencies, determine the economic cost/benefit of *SHELL* testing as a means to protect the smallholder seedling supply chain, and demonstrate whether *SHELL* testing operations can cost-effectively scale to support the national PSN/PRN smallholder green biofuel initiative.

Previous surveys of smallholder non-*tenera* contamination rates were limited to fruit-bearing palms and fruit form prediction by visual inspection of bisected fruits for shell thickness and the presence of fibres on the shell, a labour-intensive method with inherent ambiguity. For example, in a survey of 231 smallholdings in Rokan Hulu regency, Riau province, *dura* contamination was estimated to range from 53.6% in areas managed by large investment farmers to 83.0% in areas managed by small migrant farmers (Jelsma *et al*., 2017). Here, we report a pilot study evaluating *SHELL* testing utility to guard the smallholder seed and seedling supply chain, the first genetic assessment of non-*tenera* contamination in Indonesia. We assess the accuracy of *SHELL* testing and report a contamination survey conducted in the Pelalawan and Musi Banyuasin Regencies. Finally, we report the value and economic impact of CPO and PKO production gains realised from the incorporation of *SHELL* testing into the smallholder seedling supply chain.

MATERIALS AND METHODS

Sampling Sites

Smallholdings from Musi Banyuasin and Pelalawan regencies were selected for *SHELL* testing. In these regencies, construction of the first IVO conversion plant to be supplied by local smallholdings FFB is already completed and is in production, while construction of a second is underway. Pelalawan is located in Sumatra's Riau province which provides the largest oil palm area nationally. Since smallholders manage 61.6% of Riau's oil palm planted area, Riau has the largest area cultivated by smallholders nationally. Pelalawan manages 164 000 ha (9.30%) of the total 1.76 million hectares smallholder managed area of Riau, 5.73% of the 2.86 million hectares total planted area of Riau, 2.70% of the 6.0 million hectares national smallholder-managed area and 1.10% of the 14.6 million hectares total national planted area (DJP, 2022). Musi Banyuasin, South Sumatra province, has the third largest area cultivated by smallholders (122 000 ha, representing 23.40% of the total 522 000 ha smallholder managed area of Sumatera Selatan, 10.94% of the 1.11 million hectares total planted area of South Sumatra, 2.00% of national smallholder managed area and 0.80% of total national planted area) (DJP, 2022).

Sample Collection

Leaf samples from 5062 oil palms were randomly sampled from 81 smallholdings in 13 of 15 sub-regencies of Musi Banyuasin. Leaf samples from 4417 oil palms were randomly sampled from 74 smallholdings collected from 5 of 12 sub-regencies of Pelalawan regency. The selection of the combined 155 smallholders from both regencies, established between 2001 to 2020, was assisted by the corresponding regency estate crops department. On average, 61 palms were sampled at each smallholder site by using a barcoded leaf collection device (Orion Biosains "leaf punch"), representing ~22% (61/272) of the palms present on a typical 2 ha smallholding. Quick response (QR) barcodes were tracked in a laboratory information management system through all steps of the automated DNA testing process to provide reliable mapping of test results back to tissue source palms.

DNA Extraction and Analysis

DNA was extracted using standard DNA isolation protocols. Optimised high-throughput two-colour fluorescent PCR-based assays that resolve homozygous wild-type, homozygous variant or heterozygous genotypes were performed for several *SHELL* fruit-form determining single nucleotide variants known to be present in commercial planting materials (Ooi *et al.*, 2016; 2023; Singh *et al.*, 2020). All DNA processes were performed in an ISO 17025 accredited laboratory. Successful genotype results (meaning that all tested variants were successfully genotyped in a given sample) were generated in 98.5% of the samples (9341/9479). Palms were categorised as *dura*, *pisifera* or *tenera* based on the determined genotype at each variant position, as described (Ooi *et al.*, 2016). The categorisation of phenotypes into seed producer *tenera* or *dura* versus illegitimate *tenera*, *dura* or *pisifera* is described below.

Statistical Methods

Statistical significance of the bimodal distribution of the percentage of planting sites *vs*. non-*tenera* contamination rates per planting site was confirmed by Welch's 2-sample t-test assuming unequal variance that compares the location parameters of two statistical populations to test the (null) hypothesis that the two populations have equal means. All other statistical calculations were performed using standard functions in Microsoft Excel.

RESULTS AND DISCUSSION

SHELL Testing Validation

The technical performance of high-throughput *SHELL* genotyping assays was validated in two independent studies utilising blinded control leaf samples of adult palms with known fruit form phenotypes. First, 72 replicated measurements were determined from 13 palms for a total of 936 tests (Ooi *et al.*, 2023). The leaf sample genotype call rate (*i.e.*, genotype called for all tested *SHELL* variants) was 97.6% (914/936), and the reproducibility of called genotypes was 100.0% (914/914). Second, 378 DNA samples [207 field palms from Pelalawan, 59 field and 44 nursery palms from Musi Banyuasin, and 68 adult blinded control palms from Pusat Penelitian Kelapa Sawit (PPKS)] were genotyped four independent times. The genotype call rate was 100.0% (1512/1512), and the reproducibility of genotypes was 100.0% (1512/1512). Combined, the genotype call rate was 99.1% (2426/2448), and reproducibility was 100.0% (2448/2448).

To determine the accuracy of fruit form prediction, 11 *dura*, 11 *pisifera* and 11 *tenera* palms were sampled in triplicate by scientists from PPKS (biological replicates). Leaf collection device barcodes (Materials and Methods) were anonymised and submitted for blind testing at Orion Biosains. Of 94 tested samples (5 punches lacked leaf material), 92 lab predicted phenotypes were concordant with field-recorded phenotypes. One *dura* phenotyped palm tested as a *tenera* and one *tenera* phenotyped palm tested as a *dura*. To explore whether these were due to genotyping error or minor sample recording/phenotyping error in the field, a DNA plate including the two discordant samples was genotyped again, in triplicate. All three additional replicated genotype results for each of the 68 re-tested palms matched the original genotype call. At the time genotyping was performed, it was not possible to re-phenotype the two discordant palms. However, given the 100% reproducibility of multiple re-genotyping events, the two discordances were likely due to mis-phenotyping of *dura* or *tenera* fruits, which can be difficult to physically distinguish and is estimated to occur in approximately 5% of visual phenotyping calls (Singh *et al*., 2013). Therefore, the accuracy of genotype-based fruit form prediction after field collection error correction was 100%.

Seed Garden *Dura* and Illegitimate Planting Material Rates

The 13 Musi Banyuasin and five Pelalawan sub-regencies surveyed represent 88.80% and 85.50% of smallholder planted areas, respectively (*Figure 1*). Overall smallholder non-*tenera* contamination in the two regencies substantially deviated from the Indonesian National Standard (SNI 8211:2015) and Kepmentan No. 26/2021, and they were markedly similar to one another. Planting site-to-site variation was high, ranging from 100% pure *tenera* palms to 100% non-*tenera* contamination in both regencies. In Musi Banyuasin, average non-*tenera* contamination was 45.66% (41.53% *dura* and 4.13% *pisifera*). High *pisifera* content indicated a legitimacy issue. In Pelalawan, average non-*tenera* contamination was 47.67% (46.72% *dura* and 0.95% *pisifera*). Only 13 sites in Musi Banyuasin (16.00%) and 11 sites in Pelalawan (14.90%) were compliant with the Indonesian SNI 8211:2015 standard of ≤2% non-*tenera* contamination (*Figure 2*). Average rates of *dura* contamination were comparable to those measured for large investment smallholder farmers in Rokan Hulu regency, Riau province (Jelsma *et al*., 2017). A supply chain purity survey in Malaysia, which evaluated *tenera* purity in 10 244 samples, found 10.90% non-*tenera* in independent smallholders and nurseries. The same team reported similar results (12.80% contamination) when the study was expanded to cover all industry sectors (>1.1 million samples) (Ooi *et al*., 2023; Singh *et al*., 2022).

A histogram of planting sites plotted by overall non-*tenera* contamination displayed a highly resolved bimodal distribution. A total of 28.4% of sites fell into the 'left peak' of lower overall non-*tenera* contamination (5.2% average non-*tenera*). The remaining 71.6% fell into the 'right peak' of very high non-*tenera* contamination (63.5% average non-*tenera*) (*Figure 3*). Welch's 2-sample t-test assuming unequal variance confirmed the statistical significance of the bimodal distribution above *vs*. below 30% non-*tenera* contamination ($t = 1.976$, $p = 9.60 \times 10^{-58}$). Of 248 *pisifera* palms detected, 246 (99.2%) were observed in 'right peak' planting sites, suggesting planting sites in the 'left peak' were supplied primarily with legitimate planting material, while planting sites in the right peak were supplied entirely with illegitimate planting material (*Figure 3*).

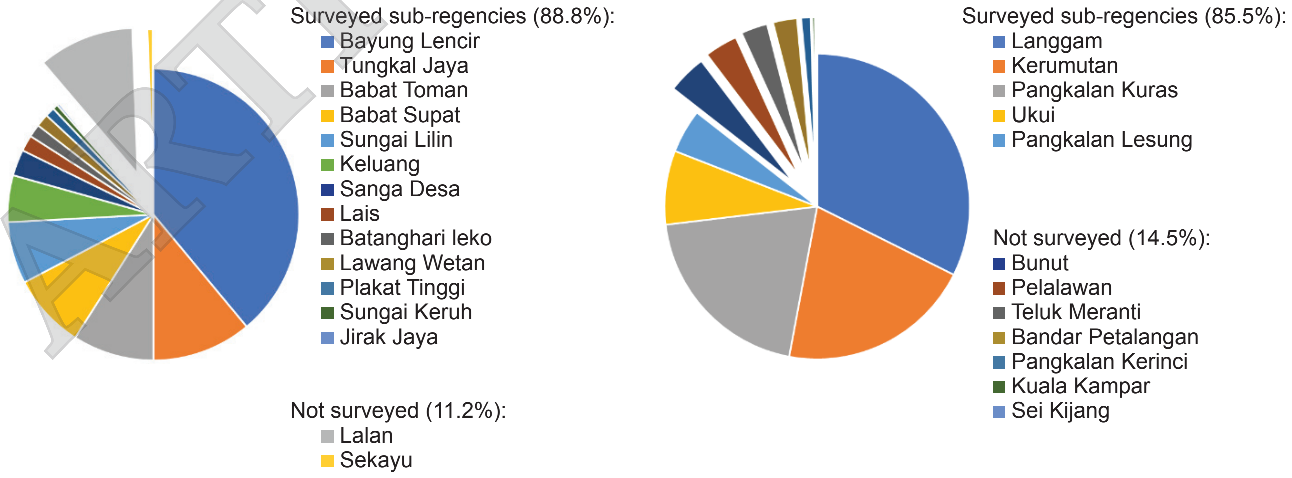


Figure 1. Percentages of Musi Banyuasin and Pelalawan regencies surveyed for the SHELL *DNA Census. Field planted palms from 13 sub-regencies (88.8% of smallholder planted area) was surveyed in Musi Banyuasin (left). Palms from 5 sub-regencies (85.5%) were surveyed in Pelalawan (right). Sub-regencies are sized by their percentage of total oil palm smallholder planted area in each regency. Sub-regencies not surveyed are shown as offset sections.*

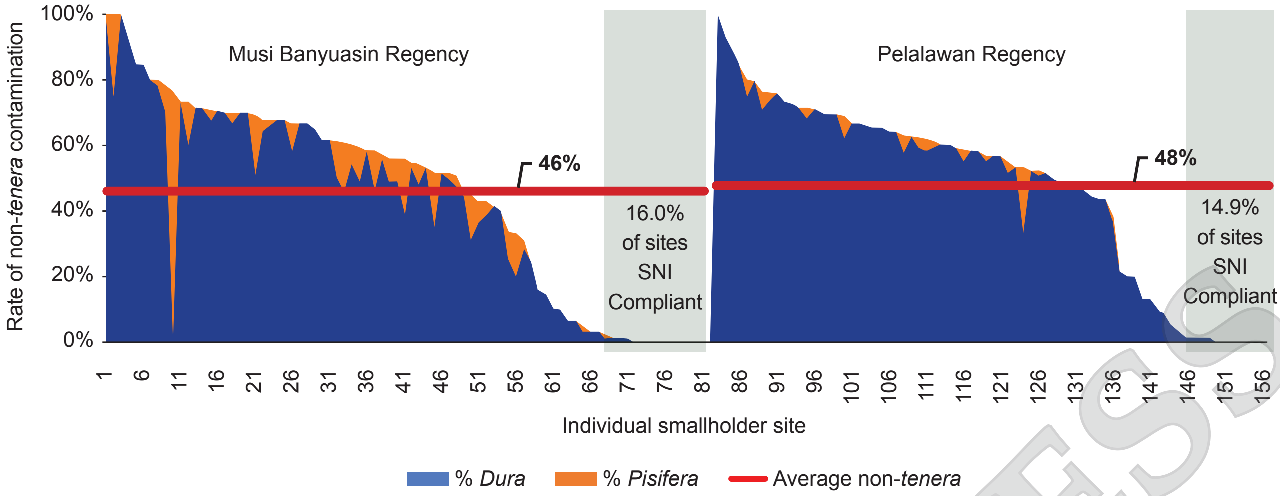


*Figure 2. Non-*tenera *percentages of Musi Banyuasin (left) and Pelalawan (right). Sub-regencies are sized by their percentage of total oil palm smallholder planted area in each regency.*

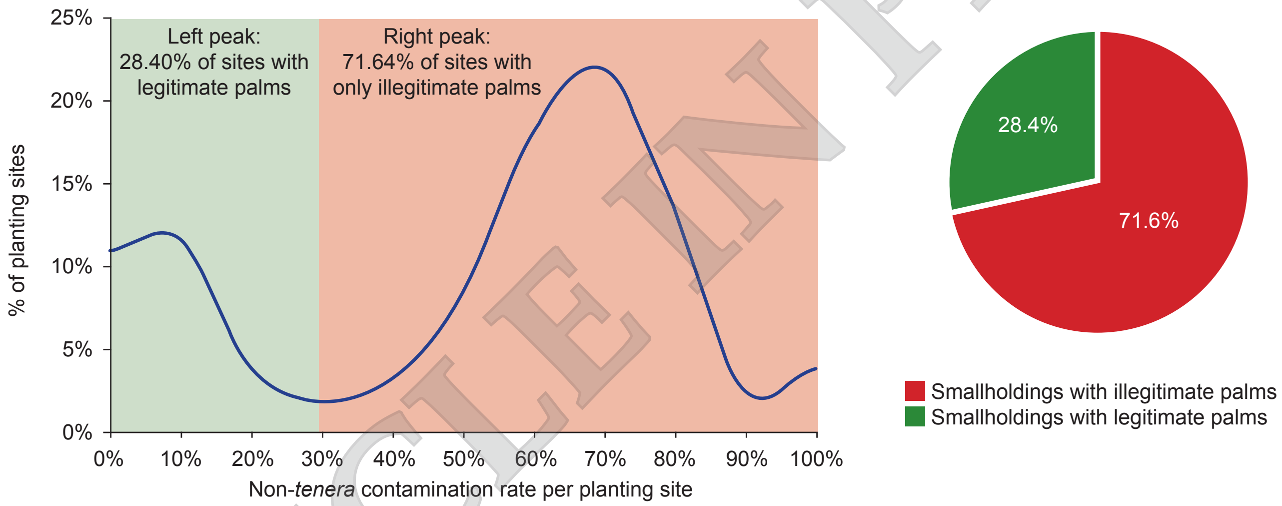


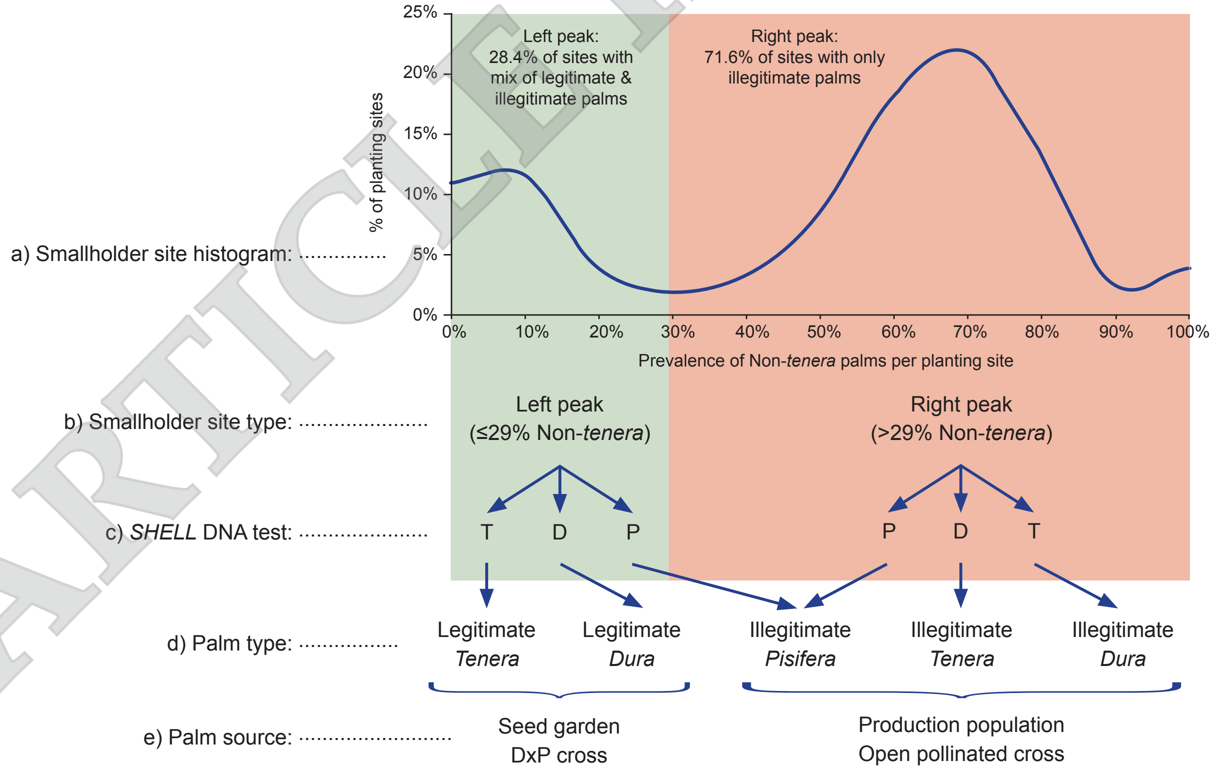
*Figure 3. Bimodal distribution of planting sites indicates legitimate and illegitimate planting material. A histogram of smallholder planting sites binned by overall non-*tenera *contamination displays a bi-modal distribution. Sites supplied primarily with legitimate material (left peak) are distinct from sites which were likely supplied with illegitimate material (right peak). The pie graph depicts a fraction of smallholder sites supplied with legitimate (green) or illegitimate material (red).*

Rates of Legitimate *Tenera*, Legitimate *Dura*, Illegitimate *Tenera*, Illegitimate *Dura* and Illegitimate *Pisifera*

Five oil palm productivity types are present in production fields, two of which originate from legitimate materials (*i.e.*, progeny tested DxP crosses at seed companies), and three of which originate from illegitimate materials (*i.e.*, undesirable open pollination of production palms) (Cochard *et al.*, 2001). Legitimate materials include two palm productivity types: Intended 'seed garden *tenera*' resulting from DxP crosses, and unintended 'seed garden *dura*' resulting from the selfing of mother *dura* palms, or intercrosses between highly related *dura* palms in the maternal seed garden. Therefore, *pisifera* palms are almost never present in seed company provided material (Hartley, 1988; Rajanaidu *et al.*, 2000). Illegitimate material typically has three productivity types (*dura, tenera* and *pisifera*) which originate from open pollination of production populations. Of the five productivity types, only 'seed garden *tenera*' is desirable, while the other four types are undesirable as they have lower FFB production as the result of inbreeding depression, as well as lower mesocarp production from the suboptimal inheritance of *SHELL* alleles (*Figure 4*) (Cochard *et al.*, 2005; Corley, 2005; Hardon, 1970; Luyindula *et al.*, 2005; Singh *et al.*, 2022).

To determine the prevalence of each of the five productivity types in the survey, we assumed palms present in planting sites with >29% non-*tenera* contamination (*i.e.*, in the 'right peak') were supplied from sources providing illegitimate materials. Therefore, *tenera, dura* and *pisifera* palms observed in these sites are each considered illegitimate. Similarly, we assumed palms present in planting sites with ≤29% non-*tenera* contamination (*i.e.*, in the 'left peak') were supplied from sources providing legitimate materials, except the two detected *pisifera* palms (*Figure 4*).

Rates of all five productivity types were determined for each smallholder site, and the averages of these rates were determined for smallholdings in each sub-regency in Musi Banyuasin and Pelalawan. Sub-regency averages were then weighted by the total oil palm smallholder planted area in the sub-regency. On a weighted average basis, 73.80% (3.30% illegitimate pisifera, 43.50% illegitimate *dura*, 26.30% illegitimate *tenera*, 0.68% legitimate *dura*) of palms in Musi Banyuasin smallholdings were of a low-productivity type (*Figure 5*). Unweighted averages were 4.10% illegitimate *pisifera* (207 palms), 40.30% illegitimate *dura* (2018 palms), 26.00% illegitimate *tenera* (1300 palms) and 1.20% legitimate *dura* (62 palms). Similarly, 72.60% (1.10% illegitimate *pisifera*, 44.00% illegitimate *dura*, 25.70% illegitimate *tenera*, 1.80% legitimate *dura*) palms in Pelalawan smallholdings were of a low-productivity type (*Figure 5*). Unweighted averages were 0.90% illegitimate *pisifera* (41 palms), 45.00% illegitimate *dura* (1951 palms), 26.50% illegitimate *tenera* (1148 palms) and 1.70% legitimate *dura* (73 palms). Legitimate seed garden *tenera* in smallholdings in Musi Banyuasin and Pelalawan were 26.20% and 27.40%, respectively, well below the required 98.00% *tenera* purity of Indonesian SNI standard and Kepmentan No. 26/2021. In open pollinations, resulting in illegitimate progeny, maternal palms may be either *dura* or *tenera* (but not *pisifera*) while paternal palms may be *dura, tenera* or *pisifera*. Therefore, even in a population with all fruit form types equally represented (which is not expected in open pollinated fields due to the low occurrence of *pisifera*), one would expect a higher proportion of illegitimate *dura* and a lower proportion of *pisifera* (when possible), relative to 1:2:1 (D:T:P) *tenera* x *tenera*, 1:1 (D:T) *dura* x *tenera* or 1:1 (T:P) *tenera* x *pisifera* ratio. Furthermore, as *dura* and *pisifera* representation in the population increases and decreases, respectively, there will be a natural shift in the population in favour of illegitimate *dura*



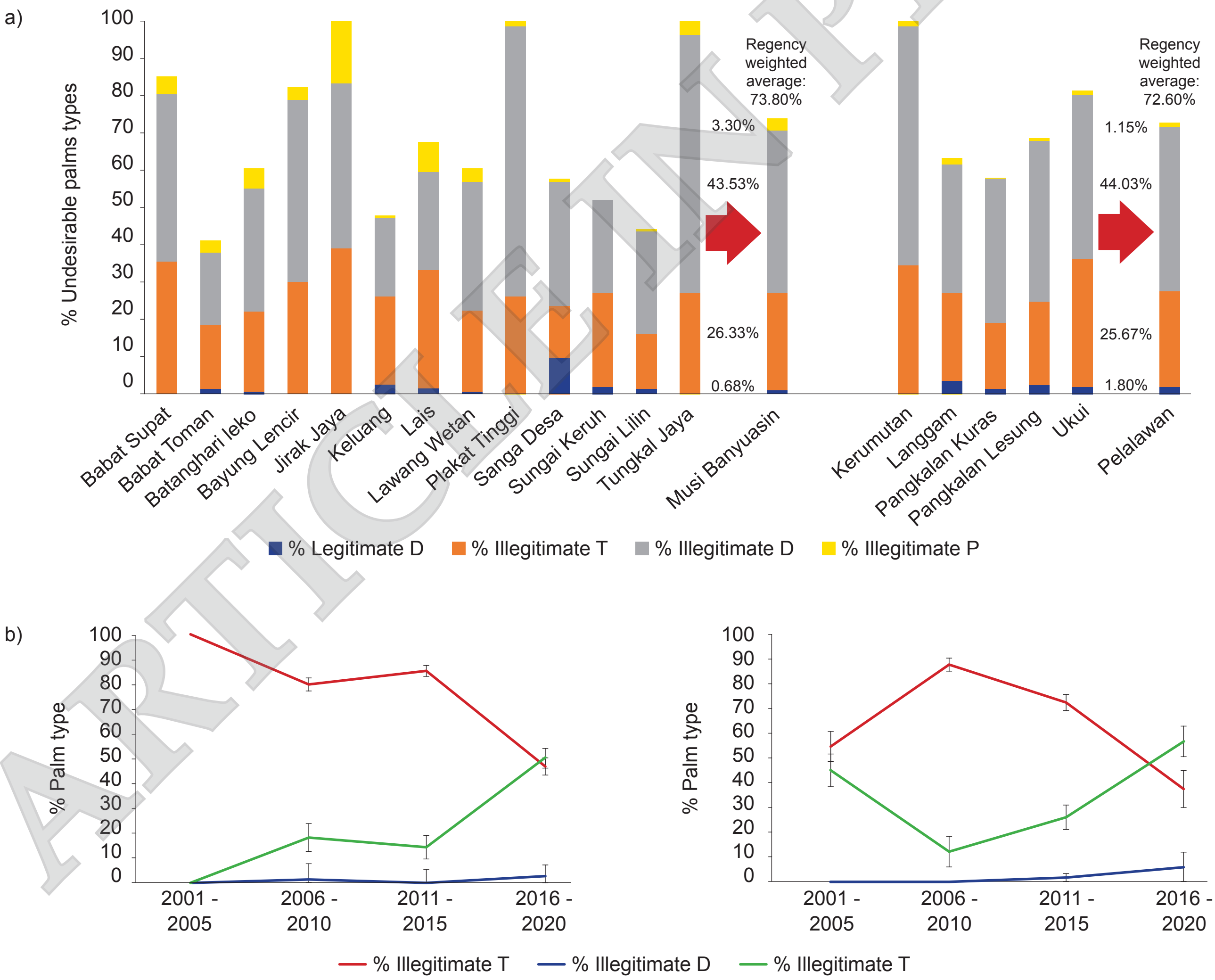
Note: T - *tenera*; D - *dura*; P - *pisifera*.

*Figure 4. Determining rates of five oil palm productivity types. (a) Histogram of smallholder sites sorted by non-tenera contamination. (b) Smallholder site types: Sites with ≤29% and sites with >29% non-*tenera *contamination. (c) and (d) SHELL test results from each site type can be mapped to the 5 palm productivity types based on the assumption that left and right peak sites are supplied from sources providing legitimate or illegitimate material, respectively. (e) Legitimate* vs. *illegitimate palm sources.*

relative to illegitimate *tenera*. This behaviour is reflected in the relative proportions of illegitimate *dura* and illegitimate *tenera* observed (*Figure 5a*). Compared to sites planted in 2006 to 2015, legitimate *tenera* rates have increased at sites planted in 2016-2020 in both regencies, likely due to improvements in the quality of planting materials in more recent years (*Figure 5b*). This does not correlate with an associated decline in legitimate *dura* rates because even in controlled DxP crosses, legitimate *dura* will still be obtained at low levels due to self-pollination of *dura* maternal palms.

Relative FFB, CPO and PKO Production Gains with *SHELL* Testing

FFB, CPO and PKO gains in Musi Banyuasin and Pelalawan regencies. A recent publication concluded that in comparison to seed garden *tenera*, three of the undesired palm types (seed garden *dura*, illegitimate *dura*, and illegitimate *tenera* palms) suffering from various degrees of in-breeding depression will produce lower FFB, CPO and PKO yields (Singh *et al.*, 2022). The study revealed that FFB yield potential for *dura* resulting from a DxP cross designed for seed production is 62.5%, lower than that of illegitimate *dura* and illegitimate *tenera* which are each 70.0%. PKO yield potential for all three undesired types matches the FFB yield potential. The CPO oil yield potential of the same *dura* is 43.8% while that of the illegitimate *dura* and illegitimate *tenera* is 49.0% and 70.0%, respectively. Such vast differences in the yield of undesired types, in combination with surveyed palm type frequency rates among smallholders in both regencies, could indicate the relative productivity gain if the four low-productivity palm types could be identified and removed from the supply chain before field planting.



Note: D - *dura*; T - *tenera*; P - *pisifera*.

Figure 5. Rates of four contaminant low-productivity oil palm types in Musi Banyuasin and Pelalawan. (a) Rates are plotted for sub-regencies in Musi Banyuasin (left panel) and Pelalawan (right panel). Overall weighted average rates are plotted in the right most bar. (b) Percent illegitimate palms, legitimate dura *palms and legitimate* tenera *palms for all smallholdings in Musi Banyuaisn (left) and Pelalawan (right) over 5-year intervals spanning 2001 to 2020. Error bars represent 95% confidence intervals.*

Based on the actual census rate for each of the palm productivity types (*Figure 5*), productivity gains were determined by comparing the actual reported productivity of Musi Banyuasin and Pelalawan to the expected productivity of these regions if *SHELL* testing were deployed. Calculations by which FFB, CPO, PKO and relative yield potential, as well as expected gains, are provided in the caption to *Table 1*. We estimate that *SHELL* testing would increase smallholder FFB production by 31% and 28% in Musi Banyuasin and Pelalawan, respectively, and this would directly translate to a 31% and 28% increase in smallholder income. Similarly, CPO production arising from smallholder derived FFB would increase by 49% and 46% while PKO productivity would increase by 31% and 28% in the two regencies, respectively.

FFB, CPO and PKO gains in Indonesia. To determine relative production gains in FFB, CPO and PKO made possible by incorporating *SHELL* testing into the seed and seedling supply chain for the smallholder replanting program across all of Indonesia, we assumed that contamination throughout the country is similar to that directly measured in the Musi Banyuasin and Pelalawan surveys (*Table 1*). We estimate that *SHELL* testing applied nationally would lower contamination by 37-fold (from 73.2% to less than 2.0%) and increase the production of FFB, CPO and PKO in the smallholder sector by 30.0%, 48.0% and 30.0%, respectively (*Figure 6*).

Value of CPO and PKO Production Gains with *SHELL* Testing

To determine the economic gains of incorporating *SHELL* testing into the smallholder seedling supply chains in Musi Banyuasin and Pelalawan, we first determined the actual quantity of CPO and PKO produced by smallholders in these regencies for a seven-year period from 2017-2023. We then determined the average price (local delivery) for CPO and PKO paid annually in this time period and computed the dollar value of smallholder production. Finally, we determined the value of the additional production that would have resulted if *SHELL* testing had been deployed in the past.

TABLE 1. NATIONAL POTENTIAL RELATIVE YIELD GAINS IN SMALLHOLDINGS ARE MADE POSSIBLE WITH *SHELL* TESTING

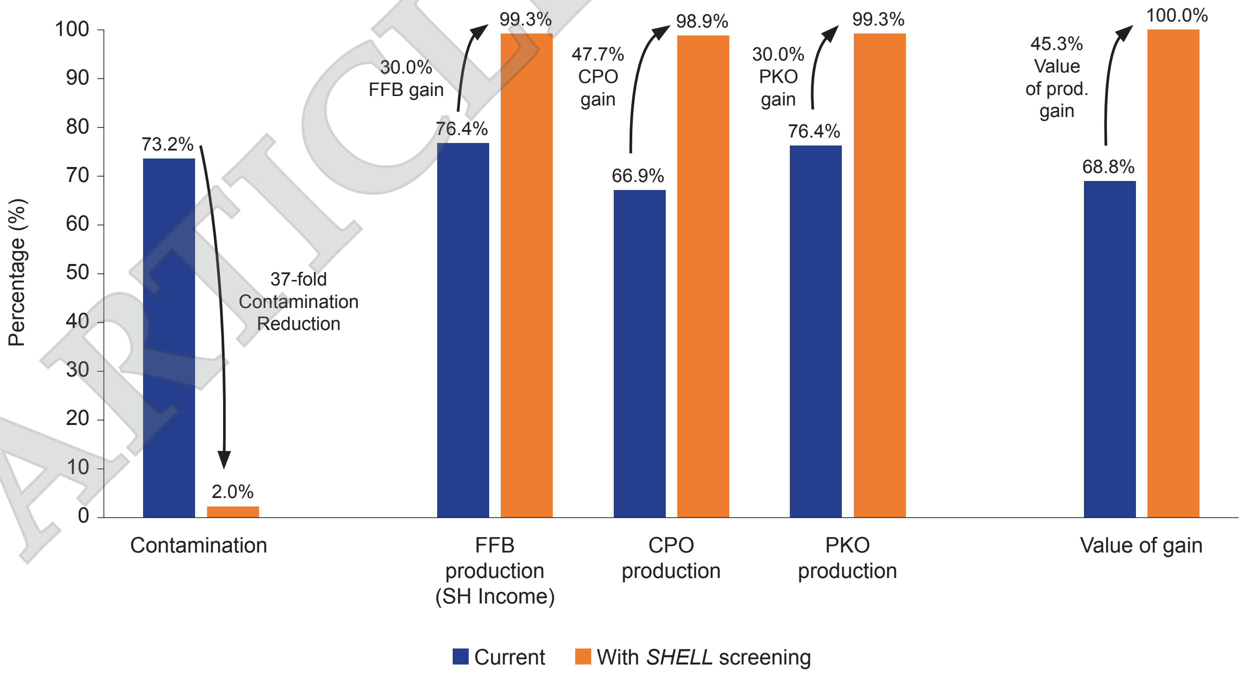
		a	b	c	d	e	f	g	h
	Palm productivity type	**Census rate (a)**	**FFB yield (b)**	***SHELL* factor (c)**	**CPO yield (=b*c)**	**PKO yield (=b)**	**FFB yield potential (=a*b)**	**CPO yield potential (=a*d)**	**PKO yield potential (=a*e)**
Yield potential (*SHELL* Testing, SNI Compliant)	Legitimate *Tenera*	98.00%	100.00%	100.00%	100.00%	100.00%	98.00%	98.00%	98.00%
	Legitimate *Dura*	2.00%	62.50%	70.00%	43.80%	62.50%	1.25%	0.88%	1.25%
	Illegitimate *Tenera*	0.00%	70.00%	100.00%	70.00%	70.00%	0.00%	0.00%	0.00%
	Illegitimate *Dura*	0.00%	70.00%	70.00%	49.00%	70.00%	0.00%	0.00%	0.00%
	Illegitimate *Pisifera*	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Relative yield potential - with *SHELL* testing:						99.25%	98.88%	99.25%
National Impact - Gain from *SHELL* Testing	Legitimate *Tenera*	26.76%	100.00%	100.00%	100.00%	100.00%	26.76%	26.76%	26.76%
	Legitimate *Dura*	1.240%	62.50%	70.00%	43.80%	62.50%	0.77%	0.54%	0.77%
	Illegitimate *Tenera*	26.00%	70.00%	100.00%	70.00%	70.00%	18.20%	18.20%	18.20%
	Illegitimate *Dura*	43.78%	70.00%	70.00%	49.00%	70.00%	30.65%	21.45%	30.65%
	Illegitimate *Pisifera*	2.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Relative yield potential - Avg 2 Surveys:						76.37%	66.95%	76.37%
	Relative yield potential - with *SHELL* testing:						99.25%	98.88%	99.25%
	% gain in smallholdings:						30.00%	47.70%	30.00%

Note: '*SHELL* Testing, SNI compliant' shows expected potential yields when *SHELL* testing is implemented to allow SNI-compliant planting materials. 'National Impact – Gain from *SHELL* Testing' shows the expected net gain in small holdings upon implementation of *SHELL* testing when the baseline is the average result of two regency census rates. FFB Yield potential (f) is the product of the Census Rate (a) times the FFB Yield for each of the palm types (b). CPO Yield Potential (g) is the product of the Census Rate (a) times the CPO Yield for each of the palm types (d). PKO Yield Potential (h) is the product of the Census Rate (a) times the PKO Yield for each of the palm types (e). The relative yield potential of FFB, CPO and PKO is the sum of the yield potentials in columns f, g and h, respectively. Expected gain in yield is the ratio of the Relative Yield Potential in the current survey divided by the Relative Yield Potential if *SHELL* testing had been in place – where all smallholder sites are made SNI compliant (<2% contamination) through the use of testing.

Historic CPO and PKO production. We constructed an estimate of smallholder CPO and PKO production for a seven-year period between 2017 and 2023 in Musi Banyuasin and Pelalawan regencies. Actual smallholder CPO production values for three years from 2017 to 2019 were supplied by the Estate Crop Department of Musi Banyuasin government. To approximate production in 2020 through 2023, we used the average production for 2017-2019. Similarly, actual smallholder CPO production values for 2019 and 2020 were supplied by the Estate Crop Department of Pelalawan Regency Government. To estimate production in 2017, 2018 and 2021 through 2023, the average of the CPO production for 2019 and 2020 years was used. To estimate PKO production for all seven years in both regencies, the ratio of the national average of PKO/CPO was used for each year where national PKO production was between 11.1% and 11.5% of national CPO production, (https://www.indexmundi.com) (*Table 2*).

Historic CPO and PKO price. Historic CPO and PKO prices were determined as the average annual CPO and PKO price (Rotterdam) minus the international delivery cost to estimate local CPO and PKO delivery prices for 2017-2023. The CPO and PKO prices in 2023 were estimated as the average of the monthly settlement prices for January through September 2023 (the most recent values available at the time of analysis), minus international costs of delivery (www.indexmundi.com) (*Table 2*).

Estimated value of production gain of CPO and PKO in the two regencies. We estimated that with a screening program that removes contaminant palms from the seedling supply chain based on *SHELL* testing, CPO production in the smallholder sector would increase on a relative basis by 49% and 46% in Musi Banyuasin and Pelalawan, respectively. Similarly, we estimated that testing planting material would increase PKO production by 31% and 28% on a relative basis in Musi Banyuasin and Pelalawan, respectively. Therefore, to estimate the quantity of additional oil that would have been produced if a DNA based testing program had been in place, the regency CPO and PKO production in each of the seven years from 2017-2023 was multiplied by the estimated relative gains from testing (*Table 2*). The value of the gains in production was determined as the estimated gain in production (in tonne) times the historic average price for each of the years (USD/t oil). In Musi Banyuasin, the annual value of additional CPO and PKO production from testing would range from USD31.09 million to USD68.47 million (USD45.50 million 7 year average), while in Pelalawan, the annual value of additional CPO and PKO production would range from USD118.08 million to USD244.22 million (USD162.01 million



Note: SH - smallholder.

Figure 6. Summary of smallholder SHELL *test survey.* SHELL *testing would lower contamination from 73.2% to less than 2.0% (37-fold). By lowering contamination, FFB production and smallholder income would increase by 30.0%. With more FFB and higher mesocarp per bunch, CPO production would increase by 47.7%, and PKO production would increase by 30.0%. The value of gain would increase by 45.3% (fifth series).*

7-year average), depending on production levels in the years and CPO and PKO price fluctuation (*Figure 7a-b*).

Estimated value of production gain of CPO and PKO nationally, with* SHELL *testing. Assuming that non-*tenera* and illegitimate contamination found in Musi Bayuasin and Pelalawan regencies was representative of smallholdings across Indonesia, we used the averages of the census rates of the five palm productivity types from the two regencies as estimates for non-*tenera* and illegitimate contamination nationally. To estimate the quantity of additional oil that would have been produced if a *SHELL* testing program had been in place in the smallholder sector across Indonesia, CPO and PKO production for the smallholder sector in each of the seven years from 2017-2023 (provided by the Direktorat Jenderal Perkebunan Kementerian Pertanian), was multiplied by the estimated relative gains made possible through testing (*Table 2*). The value of the gains in production was determined as the estimated gain in production (in tonnes) times the historic average price for each of the years (USD/t oil).

In the Indonesian smallholder sector, the value of additional CPO and PKO production from testing would range from USD4.16 billion to USD9.80 BN (7-year average USD6.41 billion) annually, depending on production levels and CPO and PKO price fluctuation over the period (*Table 2, Figure 7c*). With an estimated smallholder mature planted area of 5.14 million hectares (7-year average; provided by the Direktorat Jenderal Perkebunan Kementerian Pertanian), the annual value of the gains of smallholder production would have been USD1246/ha/yr (*Table 2*).

Economic Impact of CPO and PKO Production Gains with *SHELL* Testing

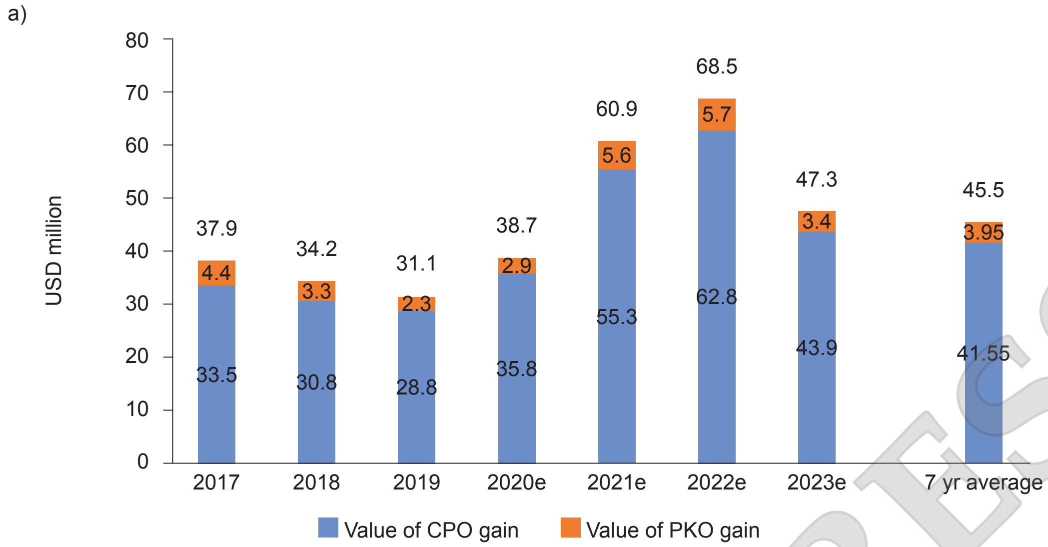
To determine the economic impact on Indonesian Gross Nation Income (GNI) of a national *SHELL* testing initiative in the smallholder replanting program, estimated gains in the production of CPO and PKO (7-year average) (*Table 2, Figure 8*) were multiplied by an economic multiplier of 1.711x (PASPI, 2016). To compute increases in national tax receipts, a corporate tax rate of 25% was assumed. To estimate the gains per hectare per year increases in production, GNI and tax receipts were divided by 5.14 million hectares, the average estimated mature planted area for smallholders in Indonesia over the seven years. Based on the smallholder contamination observed in Musi Banyuasin and Pelalawan, *SHELL* testing would increase annual oil production by USD6.41 billion/yr (USD1246/ha/yr). Gross National Income would increase by USD10.96 billion/yr (USD2131/ha/yr) and tax receipts would grow by USD2.74 billion/yr (USD533/ha/yr) (*Figure 8*).

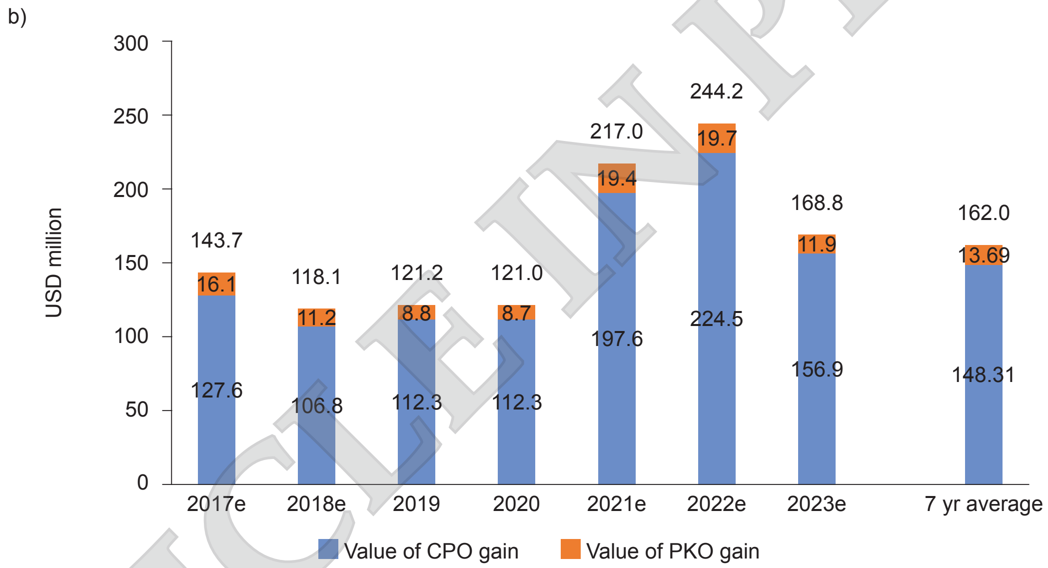
TABLE 2. NATIONAL ECONOMIC GAIN FROM *SHELL* TESTING

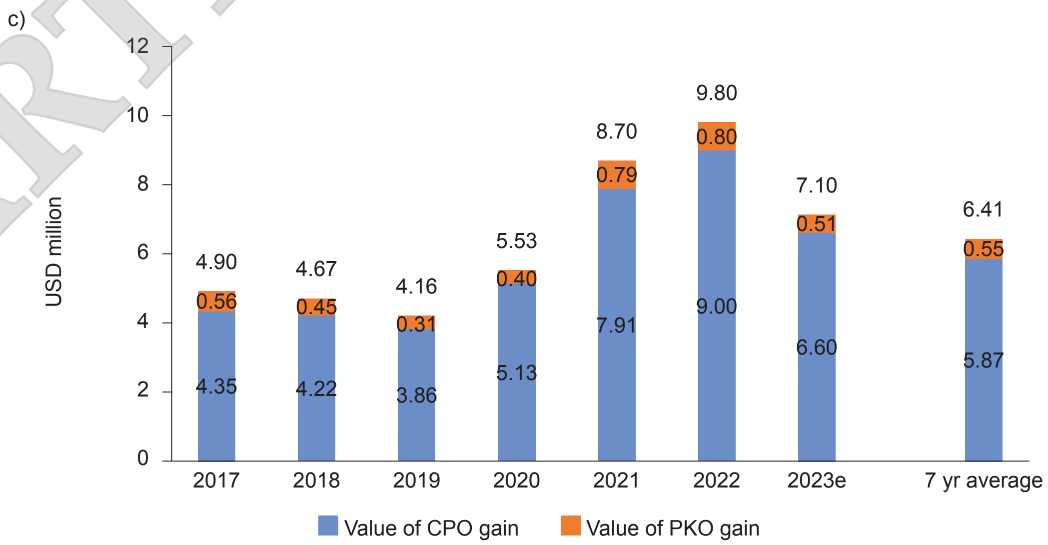
	2017	2018	2019	2020	2021	2022	2023	7-year average
Smallholder mature area (ha)	4 240 588	4 751 827	4 836 168	5 052 497	5 719 840	5 698 546	5 707 400[e]	5 143 838
SH CPO production (t)	13 191 189	15 296 801	14 925 877	15 495 427	15 503 840	15 519 234	16 273 170[e]	15 172 220
SH PKO production (t)	1 517 822	1 739 781	1 708 925	1 766 122	1 790 324	1 721 960	1 800 436[e]	1 720 767
CPO price (USD local)	691	579	542	694	1 070	1 216	850[e]	806
PKO price (USD local)	1 228	867	602	763	1 473	1 557	944[e]	1 062
CPO gain w testing (t)	6 290 573	7 294 691	7 117 806	7 389 411	7 393 423	7 400 764	7 760 299	7 235 281
PKO gain w testing (t)	454 613	521 093	511 851	528 983	536 232	515 755	539 260	515 398
Value of CPO gain (USD billion)	4.35	4.22	3.86	5.13	7.91	9.00	6.60	5.87
Value of PKO gain (USD billion)	0.56	0.45	0.31	0.40	0.79	0.80	0.51	0.55
Total revenue gain (USD billion)	4.90	4.67	4.16	5.53	8.70	9.80	7.10	6.41
Gain/ha (SH mature area)	1 156.59	983.34	860.89	1 094.60	1 521.54	1 720.12	1 244.85	1 246.46
Revenue (baseline) (USD billion)	10.98	10.36	9.11	12.10	19.23	21.55	15.53	14.05
% Revenue gain	44.70	45.10	45.70	45.70	45.30	45.50	45.70	45.60
Current revenue (USD billion)	10.98	10.36	9.11	12.10	19.23	21.55	15.53	14.05
Est. revenue (w testing) (USD billion)	15.88	15.03	13.28	17.63	27.93	31.35	22.64	20.47

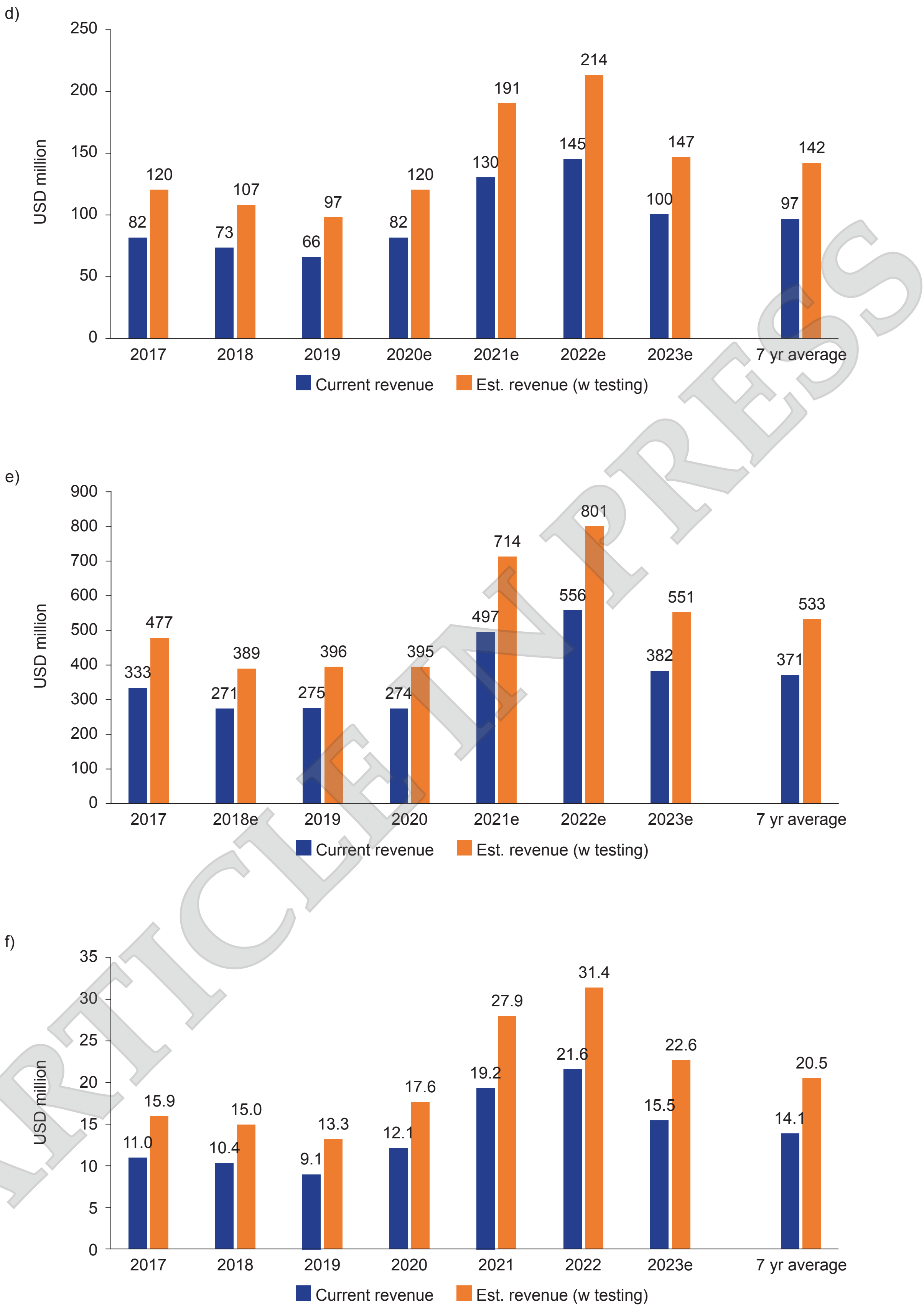
Note: Theoretical economic gains from national *SHELL* testing in the smallholder sector are determined. CPO and PKO price for local delivery is based on historic Rotterdam price minus the cost of transportation to Europe. The value of CPO and PKO gains for each year is the estimated gain from *SHELL* testing (determined in *Table 1*) times the actual production for each of the seven years. The value of the gain in production is the estimated gain (tonnes) times the price (USD/t oil).

e - estimated values for the full year of 2023 are based on January-September 2023 data; SH - smallholder.


a)
USD million
80
70
60
50
40
30
20
10
0
37.9
4.4
33.5
34.2
3.3
30.8
31.1
2.3
28.8
38.7
2.9
35.8
60.9
5.6
55.3
68.5
5.7
62.8
47.3
3.4
43.9
45.5
3.95
41.55
2017
2018
2019
2020e
2021e
2022e
2023e
7 yr average
Value of CPO gain
Value of PKO gain


b)
USD million
300
250
200
150
100
50
0
143.7
16.1
127.6
118.1
11.2
106.8
121.2
8.8
112.3
121.0
8.7
112.3
217.0
19.4
197.6
244.2
19.7
224.5
168.8
11.9
156.9
162.0
13.69
148.31
2017e
2018e
2019
2020
2021e
2022e
2023e
7 yr average
Value of CPO gain
Value of PKO gain


c)
USD million
12
10
8
6
4
2
0
4.90
0.56
4.35
4.67
0.45
4.22
4.16
0.31
3.86
5.53
0.40
5.13
8.70
0.79
7.91
9.80
0.80
9.00
7.10
0.51
6.60
6.41
0.55
5.87
2017
2018
2019
2020
2021
2022
2023e
7 yr average
Value of CPO gain
Value of PKO gain



Note: e - estimated value as described in result and discussion.

Figure 7. Estimated annual gain in production value from smallholder sector SHELL *testing. Estimated value of additional production of CPO (light-blue bar) and PKO (orange bar) is plotted for 2017-2023 and the 7-year average for Musi Banyuasin (a), Pelalawan (b) and Nationally (c). The current combined revenue from CPO and PKO (blue bar) and what revenue would have been if* SHELL *testing had been in place in the past (orange bar) is plotted for the two regencies (d, e) and nationally (f).*

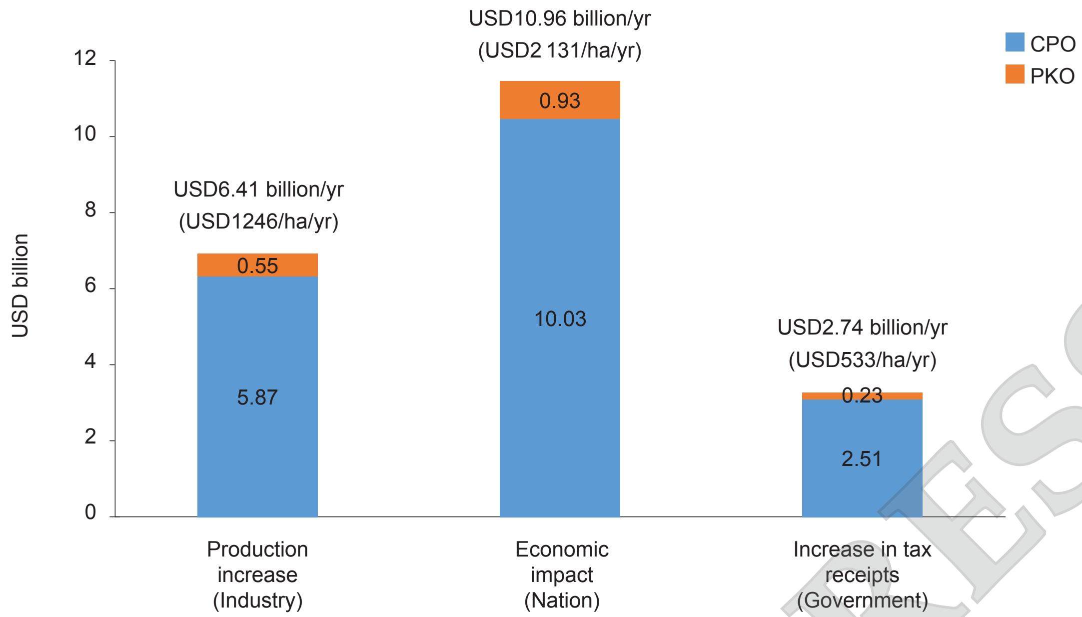


Figure 8. The annual economic impact of SHELL testing in the Indonesian smallholder replanting program. Based on average expected gains over seven years from 2017 to 2023, the estimated value of additional production of CPO (blue) and PKO (orange) (left), gains in GNI (center) and gains in tax receipts (right) are shown in billions USD. Gains in production, GNI and tax receipts are annualised. Estimated gains per hectare per year are reported above each series.

CONCLUSION

This report represents the first *SHELL* DNA based seed and seedling purity study reported for the Indonesian palm oil industry. Results from 81 smallholdings in 13 subregencies (Kecamatan) representing 88.5% of smallholding plantation area in Musi Banyuasin and 74 smallholdings in five subregencies representing 85.5% of smallholding plantation area in Pelalawan reveal high levels of non-*tenera* and illegitimate contamination: 73.8% and 72.6% in Musi Banyuasin and Pelalawan, respectively. The study highlights a fundamental problem in the secure supply of high-purity DxP planting material to independent smallholders, and likely, the results are representative of smallholders nationally.

Efforts by BRIN and PSN to establish an IVO supply chain integrating Indonesian smallholders with second generation biofuel conversion technologies rely not only on the construction of biofuel plants near areas of smallholder cultivation but also on the establishment of a smallholder replanting supply chain that is not constrained by high rates of low yielding oil palm planting material. Implementation of *SHELL* testing in the smallholder supply chain promises to provide a means to achieve significantly increased yields while also providing substantial economic gains to the palm oil industry, the government and the country of Indonesia as a whole. These gains further translate to improved sustainability in the Indonesian oil palm industry, as yield goals could be achieved from a smaller total utilised land mass.

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Muhammad A. Budiman, Abdul R. Purba, Nathan D. Lakey and Jared M. Ordway are employees and/or directors of Orion Biosains, Sdn. Bhd. and/or PT-Orion Biosains, affiliate companies of Orion Genomics, LLC that offer genetic testing to the oil palm industry. Muhammad A. Budiman, Abdul R. Purba, Nathan D. Lakey and Jared M. Ordway are employees and stockholders of Orion Genomics, LLC.

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