Cassava breeding and agronomy in Asia: 50 years of history and future directions

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In Asia, cassava (Manihot esculenta) is cultivated by more than 8 million farmers, driving the rural economy of many countries. The International Center for Tropical Agriculture (CIAT), in partnership with national agricultural research institutes (NARIs), instigated breeding and agronomic research in Asia, 1983. The breeding program has successfully released high-yielding cultivars resulting in an average yield increase from 13.0 t ha⁻¹ in 1996 to 21.3 t ha⁻¹ in 2016, with significant economic benefits. Following the success in increasing yields, cassava breeding has turned its focus to higher-value traits, such as waxy cassava, to reach new market niches. More recently, building resistance to invasive pests and diseases has become a top priority due to the emergent threat of cassava mosaic disease (CMD). The agronomic research involves driving profitability with advanced technologies focusing on better agronomic management practices thereby maintaining sustainable production systems. Remote sensing technologies are being tested for trait discovery and large-scale field evaluation of cassava. In summary, cassava breeding in Asia is driven by a combination of food and market demand with technological innovations to increase the productivity. Further, exploration in the potential of data-driven agriculture is needed to empower researchers and producers for sustainable advancement.

Key Words: Asia, cassava, conventional breeding, agronomy, new breeding techniques, data-driven agriculture, CMD.
Asia in the 1800’s and extensively cultivated in the 20th century in the Philippines, India, Indonesia and later to the rest of Asia (i.e., Malaysia, Thailand, Vietnam and China). Today, it is estimated that more than 8 million farmers grow cassava in Asia covering approximately 4.2 million ha (Howeler et al. 2013). Over the last 40 years, the demand for cassava has changed rapidly from a direct food crop to an industrial crop to use mainly as an animal feed and also processing into many different products such as sweeteners and starch as forecasted by Cock (1982), thus driving the rural economies of many countries in Asia.

In the late 1970’s, CIAT started to focus on cassava breeding and agronomy during this time of industrialization since different Asian countries differ in their objectives for cassava production, which indicates the diversity of development needed in this sector. For example, Thailand, Cambodia and Vietnam largely cultivate cassava as an industrial crop, processed and exported to China, Europe and Cambodia and Vietnam largely cultivate cassava as an important food crop in India, Indonesia, and the Philippines.

Despite its economic importance, breeding for crop improvement has been difficult in the past years that might be due to the heterozygous genetic makeup of the crop, improved varieties have been developed only recently, when compared with other crops (Ceballos et al. 2004, Kawano et al. 1978, Kawano 2003, 2011, Lynam and Byerlee 2017). Nevertheless, research on improved agronomic practices, such as identifying optimum planting time, tillage operation, preparation of planting material, weed control, intercropping and soil erosion control (Howeler 1991, Howeler and Aye 2014) has resulted in the better understanding of the crop potential to improve production. In early 1980’s, CIAT initiated the cassava breeding program in Asia jointly with NARIs and within a short period of time, a significant progress in adopting new cassava varieties was achieved as the major biotic constraints did not appear until more recently. Over the years, cassava production in Asia has increased 4.5 fold, due to a 1.8-fold increase in cultivation area and 2.5-fold increase in yield (FAO 2018, and calculated from Table 1).

Several reviews are available on cassava breeding and agronomy (Howeler et al. 2013, Howeler and Aye 2014) and this review paper focuses on the 50 years of history of cassava breeding and agronomy research, its recent developments and future research directions.

### History of cassava breeding in Asia

Cassava plays a major role in poverty alleviation, yet this crop has only recently started to receive attention from public and private research institutions. Major systematic research on improving cassava production started soon after the establishment of the International Agricultural Research Centre’s (IARC) (Raitzer and Kelley 2008). In 1969, CIAT started building a cassava germplasm collection and in 1972, established its Cassava Program by assembling a multidisciplinary team to conduct both basic and applied research. Later in 1983, CIAT established a regional cassava breeding cooperation program for Asia based in Thailand (Kawano et al. 1986, Kawano 2003, Lynam and Byerlee 2017).

Conventional breeding still continues to be the main method for cassava varietal development worldwide and had strong impact on addressing the constraints of cassava growers (Lynam and Byerlee 2017). Conventional cassava breeding methods incorporate the production of full-sib or half-sib progenies, which are evaluated through mass selection. More attention should be given to the evaluation and selection criteria of individual genotypes, as each plant is genetically distinct and later would be released as varieties to the farmers (Ceballos et al. 2015). Therefore, the selected plants with desired characteristics involves a series of clonal generations with progressively fewer genotypes, larger plot sizes and more locations (Kawano et al. 1998) leading to the release of superior varieties (Ceballos et al. 2012, 2016, Kawano 2003).

In the past two decades, with the advent of advanced molecular breeding and phenomics, significant progress has...
been made in cassava crop improvement and there have been several examples, such as developing disease resistance (Fondong 2017), reducing cyanide toxicity (Bouis et al. 2011), enhancing nutritional value (Kittipadakul et al. 2017), and improving starch yield and quality (Karlstrom et al. 2016). These technologies have also increased fundamental knowledge related to breeding, planting, nutrition, and the processing of cassava (Becerra Lopez-Lavalle 2017, Chapuis et al. 2017, Ferguson et al. 2012, Yuniwati et al. 2015).

The cassava breeding program at CIAT has focused on a wide range of objectives from yield optimization under diverse environmental conditions to maximizing the starch quality and quantity. During the period from 1992 to 1995, CIAT reached an important milestone in Thailand, releasing a variety called Kasetsart 50 (KU50) which was initially selected by the Kasetsart University after CIAT provided the cross parents. KU50 is still grown by Thai growers occupying more than 1 million ha across South East Asia (Labarta et al. 2017, Rojanaridpiched et al. 2007, 2010). By 1995, CIAT had made notable progress in breeding improved cassava varieties with superior qualities, specifically with fresh root yield (FRY) and dry matter content (DMC) (Kawano 2003). As the genetic gains in yields (FRY and DMC) have slowed down, cassava breeders have shifted their attention to other value-added traits that are easier to breed such as nutritional quality (Ceballos et al. 2016, Ceballos and Hershey 2016).

However, to date, advanced genomic and genetic tools have contributed in describing the crop’s genetic diversity (Bradbury et al. 2013, de Oliveira et al. 2014, Fregene et al. 2003), diagnostics of cassava pest and diseases (Bart et al. 2012, Leggs et al. 2011), gene expression studies (Amuge et al. 2017, Ballen-Taborda et al. 2013), resistance to CMD in African germplasm (Egesi et al. 2006, Okogbenin et al. 2007), as well as post-harvest physiological deterioration (PPD) gene profiling in cassava roots (Reilly et al. 2007, Wilson et al. 2017). Therefore, recent developments in genomic research will help facilitate cassava breeding by providing knowledge and tools for attributes or traits for cassava improvement (de Oliveira et al. 2012, Wang et al. 2014, Wolfe et al. 2016).

In the past 50 years, CIAT’s cassava breeding program has identified germplasm on specific traits of interest and developed elite progenies (Kawano et al. 1978) which were then distributed to the national breeding programs in several Asian countries (Kawano et al. 1986, Lynam and Byerlee 2017). In the following sections, we focus on country-specific breeding programs, most of which are in collaboration with CIAT.

**Thailand**

Cassava improvement and production in Thailand has been continued for more than 40 years. The breeding program was started by the Department of Agriculture in 1937 with the germplasm introduced from Malaysia and the Philippines and later from the Virgin Islands and Colombia. Initially, the breeding objectives were focused on FRY, dried root yield, starch content, harvest index and plant type (Kawano 2003, Kittipadakul et al. 2017). The current breeding program aims at developing varieties suitable for industrial purposes that are both edible and resistant to pest and diseases. As cassava is a heterozygous plant, attempts have been made to develop improved cassava hybrids with increased yield as like the success with maize. This process has been challenging due to high inbreeding depression that renders selfed lines of cassava with less reproductive potential. Experiences gained on flowering induction and synchronization in Thailand were shared with cassava breeders in other Asian countries (Kittipadakul et al. 2017) as they are identified as the major bottlenecks in cassava breeding.

Rayong 1 was the popular cassava landrace grown in Thailand from 1950 till 1970. Breeding attempts were made in combination of local varieties, Rayong 1 and Jek-Kui and released varieties including Rayong 60, Sriracha 1, Rayong 72 and Kasetsart 50 (KU50). Since 1975, 19 cassava varieties have been released in Thailand (Table 2), with many cultivated throughout Asia. In 1983, a large number of cassava germplasm was imported from CIAT-HQ, Colombia to the Rayong Field Crops Research Center (RYFRCRC) under the Thai-CIAT joint breeding program. In the early 1990s, the breeding program was started using this imported germplasm. Furthermore, a cooperation between CIAT and the Department of Agriculture (DOA) under the Ministry of Agriculture and Cooperatives was established in 1983 to include germplasm exchange from CIAT (collection at RYFRCRC) as parents (Kawano 2003, Rojanaridpiched et al. 2007, 2010). Among other cassava varieties released, KU50 is a good example of successful cassava breeding in Thailand, with its higher yield and starch content than Rayong 1. Currently, KU50 is cultivated on more than 1 million hectares in Thailand and Vietnam (as KM94) and also cultivated in Indonesia, Cambodia, Myanmar, and the Philippines (Gracen et al. 2017). In 2017, with the research data from 39 trials conducted across Thailand, the Thai Tapioca Development Institute (TTDI) and Kasetsart University, jointly released Huay Bong 90 (HB90), a cassava variety with a fresh root yield of 31.8 t ha⁻¹ (45% higher than Rayong 1) whereas KU50, HB60, and HB80 had 38, 37, and 42% more fresh root yield, respectively. The average starch content of HB90 was 25.7%, which was similar to that of HB80. HB90 has an upright plant type, which is suitable for mechanical harvesting. In 2017, the TTDI distributed 633,850 HB90 stems to farmers (unpublished data).

The success of cassava improvement in Thailand was possible with the strong cooperation between government and private sectors. The Department of Agricultural Extension, the Cooperative Promotion Department, and the TTDI Foundation played a major role in distributing new varieties to Thai farmers (Rojanaridpiched and Srinives 1986). The RYFRCRC under the DOA, a primary research centre of
| Variety name  | Pedigree/parents                        | Traits of interest                  | Yield (t ha\(^{-1}\)) | Starch content (%) | Year of registration or release | References                  |
|---------------|----------------------------------------|-------------------------------------|------------------------|--------------------|-------------------------------|-----------------------------|
| Rayong 1      | Landrace                               | Highly adapted to environment       | 20.1                   | 18.3               | 1975                          | Sarakam et al. 2000         |
| Rayong 3      | MMex55 × MVen307                       | High starch content                 | 17.1                   | 23–28              | 1983                          | Sarakam et al. 2000         |
| Rayong 2      | MCol13 × MCol22                        | Moderate hydrocyanic acid content   | 25.6                   | 18.3               | 1984                          | Sarakam et al. 2000         |
| Rayong 60     | MCol1684 × Rayong 1                    | Early bulking                       | 26.3                   | 20–25              | 1987                          | Sarakam et al. 2000         |
| Rayong 90     | CMC76 × V43                            | High starch content                 | 23.8                   | 24–29              | 1991                          | Sarakam et al. 2000         |
| Rayong 5      | 27-77-10 × Rayong 3                    | High yield                          | 27.5                   | 23–27              | 1994                          | Sarakam et al. 2000         |
| Rayong 72     | Rayong 1 × Rayong 5                    | High yield, drought tolerant         | 31.9                   | 20–24              | 1999                          | Sarakam et al. 2000         |
| Rayong 7      | CMR30-71-25 × OMR29-20-118             | High yield, drought tolerant         | 38.1                   | 23–29              | 2005                          | Prammanee et al. 2010       |
| Rayong 9      | CMR31-19-23 × OMR29-20-118             | High yield and starch content        | 30.6                   | 24–31              | 2006                          | Prammanee et al. 2010       |
| Rayong 11     | Rayong 5 × OMR29-20-118                 | High starch content                 | 29.8                   | 26–32              | 2010                          | DOA 2013                    |
| Rayong 86     | Kasetsart 50 × Rayong 11               | High yield and starch content        | 28.2                   | 26–33              | 2013                          | Hansethasuk et al. 2016    |
| Srincha 1     | MKU2-162 × Rayong 1                    | High yield                          | 20.1                   | 21.9               | 1990                          | Sarakam et al. 2000         |
| Kasetsart 50  | Rayong 90 × Rayong 1                   | Highly adapted to environment, high starch content | 32.5 | 24.9 | 1992 | Prammanee et al. 2010 |
| Kasetsart 72  | Rayong 5 × OMR29-20-118                | Highly adapted to environment, high yield | 31.3 | 27 | 2015 | Chaisri et al. 2013 |
| Huay Bong 60  | Kasetsart 50 × Rayong 5                | High yield and starch content        | 36.3                   | 25.1               | 2003                          | TTDI 2018                   |
| Huay Bong 80  | Kasetsart 50 × Rayong 5                | High yield and starch content        | 34.4                   | 27.3               | 2008                          | Kittipadakul et al. 2012   |
| Huay Bong 90  | MKUC34-114-235 open-pollinated         | Straight plant type, easy to mechanically harvest, high yield and starch content | 31.8 | 25.7 | 2017 | Unpublished data |
| Pirun 1       | Huay Bong 60 × Hanatee                 | High yield                          | 41.3                   | 28.7               | 2014                          | Unpublished data            |
| Pirun 2       | Huay Bong 60 × Hanatee                 | Moderate hydrocyanic acid content   | 36.3                   | 24.7               | 2015                          | Unpublished data            |

1 All Rayong varieties are from the breeding program of the Rayong Field Crops Research Center (RYFCRC), Department of Agriculture (DOA), Ministry of Agriculture and Cooperative; 2 Srincha 1 and Kasetsart (KU) varieties are from Kasetsart University; 3 Huay Bong varieties are from the breeding program at Kasetsart University and Thai Tapioca Development Institute; 4 Pirun varieties are from the breeding program at The National Science and Technology Development Agency (NSTDA) and Mahidol University.
cassava in Thailand, maintains a duplicated set of the CIAT cassava core collection of 628 accessions. The RYFCRC has developed and released ten cassava varieties for industrial purpose and one sweet variety for human consumption (Table 2).

The collaboration between CIAT and Thai cassava researchers has evolved over the time as the Thai research capacity expanded and enhanced the breeding populations. Excellent germplasm has been released with a huge potential to improve the yield and increase the farmer’s income (Johnson et al. 2003, Kawano 2011). Simultaneously, the emerging biological threats, such as the appearance of mealybug in 2010 (which could be controlled by biological control agents) (Parsa et al. 2012) and the recent identification of Sri Lankan cassava mosaic virus (SLCMV) (Wang et al. 2016), requires regional and international efforts. Through the systemic approach and continuous collaboration between Thai-research institutions and CIAT, source of emerging biological threats, such as the appearance of mealybug in 2010 (which could be controlled by biological control agents) (Parsa et al. 2012) and the recent identification of Sri Lankan cassava mosaic virus (SLCMV) (Wang et al. 2016), requires regional and international efforts.

Cassava, a high potential industrial crop, is highly valued for its starch worldwide. “Waxy cassava starch”, an amyllose-free waxy mutants found in many crops and considered as a high-value trait. The relative proportions of the two components of starch (20% amylose and 80% amylopectin) strongly influence the functional properties of the starch as do most starches from other crops (Ceballos et al. 2007). In 2007, CIAT reported the discovery of a spontaneous mutation in cassava that resulted in the production of amyllose-free starch (Aiennaka et al. 2012, Ceballos et al. 2007). The TTDI and CIAT signed a joint agreement to develop commercial cassava varieties with waxy starch adapted to Thailand. The work was undertaken with the leadership of Kasetsart University and resulted in the identification of three clones with satisfactory agronomic performance, which were the first commercial cassava varieties with this trait. Waxy cassava starch has 25% higher viscosity to normal cassava and produce clearer gels that are more stable (acid and alkaline resistance, shear, refrigeration, and freeze/thaw stability) than non-waxy cassava starch (Sánchez et al. 2010).

**Vietnam**

Cassava breeding efforts in Vietnam were first reported in 1975. Significant achievements were documented after 1988 as a result of capacity building and germplasm introduction from CIAT (Kim et al. 1999, 2001). A systematic cassava breeding program began after a collaborative survey in 1991–1992, conducted by CIAT, the International Development Research Centre (IDRC), International Potato Center (CIP), and national organizations, including the Root Crops Research and Development Center (RCRDC) and Hung Loc Agricultural Research Center (HLARC) in 270 cassava cultivation sites of 43 provinces in Vietnam and collected 128 cassava varieties. These varieties, along with the materials from CIAT-HQ, China, Thailand and other countries, have been used for breeding and selection (Nguyen et al. 1995, 2012, Quyen and Kim 1995). As a result, 19 new varieties were registered in the last 20 years (Table 3). To date, all registered cassava varieties were bred through conventional approaches including open and controlled pollination and mutation breeding.

To understand the impact of cassava breeding in Vietnam, the Agricultural Genetics Institute (AGI), HLARC, Institute of Agricultural Sciences in Southern Vietnam (IAS) and CIAT carried out a second survey on cassava varietal adoption study in 2016. Genotyping by single nucleotide polymorphism (SNP) array identified a total of 152 unique cassava varieties and landraces (Le et al. 2019), which are now maintained in the field by RCRDC. The survey revealed that 85% of the total cassava area is planted to improved varieties. KM94 (KU50), bred in Thailand and released in Vietnam in 1992, remains the dominant variety occupying 45% of area and with KM419, a locally-bred variety released in 2013, already planted on 30% (161,924 ha) of the total cassava area in Vietnam, and the rest were planted with other varieties bred by Vietnam breeding programs (Le et al. 2019).

To broaden the genetic base of cassava in Vietnam, 55 elite cassava lines were imported from CIAT-HQ in 2015, which are maintained at the International Laboratory for Cassava Molecular Breeding (ILCMB) jointly established by AGI and CIAT in 2012. These lines are currently being evaluated in different eco-regions of Vietnam to determine their suitability. Recently, breeding for disease resistance has received attention after severe outbreaks of cassava witches’ broom disease (CWBD) in Central and South East regions (Graziosi et al. 2016) and SLCMV in Tay Ninh province, 2017 (Uke et al. 2018, Wang et al. 2016).

**China**

Historically, cassava breeding in China involved collecting, evaluating and testing exotic and indigenous germplasm. However, with the increase in cassava consumption and industrial demand, breeding programs started to focus on developing cold- and drought-tolerant varieties that enable farmers to cultivate cassava further north (above 25°N latitude). Other breeding objectives include meeting the growing demands of different industrial sectors, such as (1) increasing yields and starch content for the biofuel industry; (2) increasing protein and carotenoid contents for the food industry; and (3) using molecular tools to breed varieties for the biochemical industry (i.e., molecular breeding).

Over the years, numerous varieties have been released by the Chinese Academy of Tropical Agricultural Sciences (CATAS) for cassava cultivating regions in China (Table 4). SC205, a popular variety bred 30 years ago, is still cultivated on 60–70% of the total cassava plantation area. Nanzhi 199 and XX048 are becoming popular and covers 50–60% of the plantation area in the mid- and high-latitude zones, of which Nanzhi 199 is not only a high
| Variety   | Pedigree/parents                                                                 | Traits of interest                                                                 | Yield range (t ha\(^{-1}\)) | Starch content (%) | Year of registration or release | Reference          |
|----------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------|-------------------|-------------------------------|--------------------|
| KM60     | Original name Rayong 60, introduced from Thailand                                  | High yield, good root shape, early harvest, yellow flesh                             | 27–32                         | 26.4–27.8         | 1995                          | Quyen et al. 1995  |
| KM94     | Original name KU50, introduced from Thailand                                       | High yield and starch content, highly branched, prone to lodging, throughout Vietnam | 30–40                         | n.a.              | 1995                          | Quyen et al. 1995  |
| SM937-26 | Introduced from Thailand                                                           | High yield and starch content, drought resistant, suitable for marginal land         | 30–38                         | n.a.              | 1995                          | Quyen et al. 1995  |
| KM98-1   | Selected from F\(_1\) hybrid seeds, Rayong 1 × Rayong 5                         | High yield and starch content, early harvestability, good plant type, DMC: 38.6%, Tay Ninh province | 32–35                         | 27.5–28.2         | 1999                          | Kim et al. 1999    |
| KM98-5   | Selected from F\(_1\) hybrid seeds, Rayong 1 × Rayong 5                         | DMC: 40.1%, Tay Ninh province                                                       | 34.5–n.a.                     | 26.1–28.4         | 2007, 2009                    | Kim et al. 2007    |
| KM140    | Selected from F\(_1\) hybrid seeds, Rayong 1 × Rayong 5                         | Low cyanogenic content, suitable for fresh consumption, southern provinces and Cambodia | 30–50                         | n.a.              | 2007, 2009                    | Kim et al. 2015    |
| KM98-7   | Selected from F\(_1\) hybrid seeds, Rayong 1 × Rayong 5                         | Oblong leaf blade, drought resistant, suitable for marginal land, northern provinces | n.a.                          | n.a.              | 2008                          | Loan et al. 2008   |
| Sa21-12  | n.a.                                                                             | Suitable for marginal land, northern provinces                                       | 38–40                         | 28–30             | 2012                          | Nguyen et al. 2012 |
| Sa06     | Original name Rayong 9, introduced from Thailand                                  | Low branching, North and Central Highlands                                           | 36–42                         | >30               | 2016                          | Kim et al. 2015    |
| *KM419   | Selected from F\(_1\) hybrid seeds, (SM937-26 × KM60)                           | Southeastern provinces, Central Highlands and Cambodia                               | >40                           | n.a.              | 2016                          | Kim et al. 2015    |
| *HLS11   | Selected from F\(_1\) hybrid seeds, (SM937-26 × KM60)                           | DMC: >40%, erect stem, no branching, southern provinces                              | 40–42                         | >30               | 2016                          | Nguyen et al. 2016 |
| *BK      | n.a.                                                                             | Starch and fresh consumption, northern and central provinces                         | 47–52                         | 27                | 2016                          | Unpublished data   |
| *HLS10   | Selected from F\(_1\) hybrid seeds (KM146 × KM140)                              | Southeastern provinces and Central Highlands                                        | 43.2–47.3                     | 27.2              | 2016                          | Nguyen et al. 2016 |
| *HL2004-28 (KM444) | n.a.                             | DMC: 40.3%, northern provinces                                                     | 35.5–na                       | 29.0–31.2         | 2016                          | Kim et al. 2015    |
| *DT4 (Rayong 72) | n.a.                             | DMC: >40%, northern and central provinces                                           | 39.9–43.3                     | >30               | 2016                          | Kim et al. 2015    |
| *KM7     | Selected from F\(_1\) hybrid seeds from SM937-26                               | Southern and central provinces                                                      | 37.6–40.5                     | n.a.              | 2016                          | Unpublished data   |
| *STB1 (KM440) | n.a.                             | DMC: 39.2%, northern and central province                                          | 33–42                         | 28–30             | 2017                          | Kim et al. 2015    |
| *KM101   | Original name CMR29-56-101, introduced from Colombia                            | DMC: >38%, southern provinces                                                      | 37–42                         | >28               | 2017                          | Nguyen et al. 2016 |
| *10Sa01  | n.a.                                                                             | DMC: >40%, southeastern region                                                      | 38–42                         | 30                | 2017                          | Unpublished data   |

* Test production, not approved for national release; n.a. = not available; DMC = dry matter content.
Table 4. Varieties developed and released in China and their agronomic performance

| Cultivar       | Pedigree                                                                 | Traits                                                                 | Yield (t/ha) | Crop duration (days) | Starch content | Year of release | Reference                  |
|----------------|---------------------------------------------------------------------------|------------------------------------------------------------------------|--------------|----------------------|----------------|-----------------|-----------------------------|
| SC6068         | SC201                                                                     | High starch content                                                    | 20.6–24.5    | –                    | 27.0           | 1965            | Xiong et al. 2000           |
| SC124          | F₁ of nature hybrid seeds from SC205                                      | High yield, low starch, high tolerance to cold                         | 30.0–32.5    | –                    | 24.5           | 1991            | Xiong et al. 2000           |
| NZ188          | CM321-188                                                                 | High yield, low starch, poor cold tolerance                            | 22.5         | –                    | 1992           | Yan et al. 2015  |
| SC8002         | SC124 × SC205                                                             | High yield                                                             | 27.8–28.7    | –                    | 27.0           | 1994            | Xiong et al. 1995           |
| SC8013         | SC124 × SC205                                                             | High starch content                                                    | 25.3–29.5    | –                    | 28.9           | 1994            | Xiong et al. 1995           |
| GR891          | MCOL2215 × MPAN                                                           | High yield, high starch content, short duration                        | 32           | –                    | 29–31          | 1998            | Yan et al. 2015             |
| GR911          | SC124 × SC205                                                             | High yield                                                             | 43           | –                    | 27–28          | 1999            | Yan et al. 2015             |
| GR3            | 1150 hybrid seeds were introduced from Thailand field crop research center in 1994, and selected one from those hybrid seeds | High yield, high starch content                                        | 40           | –                    | 29–30          | 2007            | Yan et al. 2015             |
| GR1            | Rayong 1 × Rayong 90/KU50                                                 | High yield, high starch content                                        | 40           | –                    | 27–28          | 2008            | Yan et al. 2015             |
| GR4            | CIAT Natural hybrid seeds from PAR164 /line SMI 600                      | High yield, high starch content                                        | 41           | –                    | 26–28          | 2011            | Yan et al. 2015             |
| GR5            | Huay Bong 60 (R5 × KU50)                                                  | High yield, high starch content                                        | 39           | –                    | 29–31          | 2011            | Yan et al. 2015             |
| GR6            | CIAT Natural hybrid seeds from CM4729-2 /line SM2895-1                   | High yield, high starch content                                        | 30           | –                    | 29–30          | 2012            | Unpublished data            |
| GR7            | CIAT Natural hybrid seeds from Gc9948-1                                   | High yield, high starch content                                        | 42           | –                    | 29–30          | 2015            | Unpublished data            |
| GR8            | Line KM316 was introduced from Vietnam southern academy of agricultural sciences, HLARC (KM98-1 × KU50) | High yield, high starch content                                        | 39           | –                    | 28–29          | 2016            | Unpublished data            |
| GR9            | The wild cassava germplasm, named Singkonggaiah (elephant cassava), was introduced from the tropical rain forest of Kalimantan province, Indonesia in 2010 | High yield, high starch content                                        | 30           | –                    | 29–31          | 2016            | Unpublished data            |
| SC5            | ZM8625 × SC8013                                                           | High yield, high starch content                                        | 33.0–43      | –                    | 28.5           | 2000            | Yan et al. 2015             |
| SC6            | OMR33-10-4                                                               | High starch content, typhoon resistant, good germination               | 25.0–42      | –                    | 28.5           | 2001            | Yan et al. 2015             |
| SC7            | F₁ of nature hybrid seeds from SC205                                      | High dry matter content and high starch content                        | 42.61        | –                    | 27.3           | 2004            | Ye et al. 2007             |
| SC8            | F₁ of natural hybrid seeds from CMR38-120                                | High yield, high starch content, strong adaptability, tolerance to fertilizer, poor soil, drought weather, and typhoon resistant | 38–45        | 240                  | 30–32          | 2004            | Ye et al. 2006             |
| SC9            | Introduced from Philippines around 1820                                  | Good taste, low cyanic content, high starch content, early harvest, heavy branches | 20–35        | 210                  | 30–33          | 2005            | Yan et al. 2015             |
| SC10           | CM4042 × CM4077                                                          | High yield, high starch content                                        | 30–45        | 300                  | 30–32          | 2006            | Yan et al. 2015             |
| SC11           | Introduced from Brazil (Line named B900)                                 | High yield, low starch, stronger tolerance to fertilizer and waterlogging | 30           | 300                  | 25–28          | 2009            | Yan et al. 2015             |
| SC12           | OMR36-34-1 × ZM9247                                                      | High yield, high starch content, low cyanic content, strong adaptability, tolerance to fertilizer, drought weather, and resistance to bacterial blight and vermillion mites | 40           | 300                  | 30–32          | 2014            | Ye et al. 2014             |
| SC13           | F₁ of natural hybrid seeds from SC8013                                    | High yield, high starch content, low cyanic content, resistance to bacterial blight and vermillion mites | 43           | 240                  | 29–30          | 2015            | Ye et al. 2017             |
| SC14           | Landrace of Qionzhong Hainan China                                       | High yield, low starch, low cyanic content, strong adaptability, tolerance to PPD | 38.25        | 330                  | 23–26          | 2016            | Qin et al. 2017            |
| Guishu JS03    | Selected from F₁ population of cassava cultivar from the Balai district, Xayaburi Province, Laos | High yield, high starch content                                        | 37.5–52.5    | 300–330              | 29–30          | 2015            | Unpublished data            |
| Cultivar       | Pedigree                                                | Traits                                   | Yield (t/ha) | Crop duration (days) | Starch content | Year of release | Reference                        |
|---------------|---------------------------------------------------------|------------------------------------------|--------------|----------------------|----------------|----------------|----------------------------------|
| Guimushu 1    | Selected from F$_1$ population of line E497, introduced from TCGRI CATAS, the plant line number was GW10-E497-2, and the regional test number was E30 | High yield, high starch content          | 39–52.5      | 300–330              | 29–30          | 2016            | Wei et al. 2016                  |
| Guimushu 2    | Selected from F$_1$ population of line E497, introduced from CATAS, the plant line number was GW10-E497-10 | High yield, low starch content, no branches | 37.5–48      | 300–330              | 24–25          | 2016            | unpublished data                 |
| Guimushu 3    | Selected from F$_1$ population of line E497, introduced from CATAS, the plant line number was GW10-E497-17 | High yield, high starch content, few branches | 37.5–48      | 300–330              | 30–31          | 2016            | unpublished data                 |
| Guimushu 4    | Selected from F$_1$ population of line E497, introduced from CATAS, the plant line number was GW10-E497-19 | High yield, high starch content, few branches | 37.5–48      | 300–330              | 29–31          | 2016            | unpublished data                 |
| Guimushu 5    | Selected from F$_1$ population of SC205, the plant line number was WG10-SC205-1 | High yield, high starch content, few branches | 37.5–52.5    | 240–270              | 30–33          | 2016            | Unpublished data                 |
| Guimushu 6    | Selected from the F$_1$ population of Xinxuan 048, the new cassava variety was developed through embryo rescue, tissue culture, rapid propagation, and the test number was NK-6 | High yield, high starch content, few branches | 39–52.5      | 300–330              | 28–30          | 2016            | Unpublished data                 |
| Guimushu 7    | Selected from the F$_1$ population of Xinxuan 048, the new cassava variety was developed through embryo rescue, tissue culture, rapid propagation, and the test number was NK-7 | High yield, high starch content, good plan type, good germinates and good growth vigor | 30–37.5      | 300–330              | 29–31          | 2016            | Unpublished data                 |
| Fuxuan 01     | Using cassava variety SC124 as material and selected and bred from its variant strain by radiation mutagenesis | High yield, high starch content, stem good to storage, germinated quickly and neatly, and had high germination rate, wide adaptability, cold and drought resistance | 30–45        | –                    | 30–32          | 2005            | Yan et al. 2015                  |
| Xinxuan 048   | From natural variation of cassava germplasm ZM93-16 population | High yield, high starch content, stem germinates quickly and neatly, and had high germination rate, wide adaptability, suitable for sparse planting, intercropping and mechanical planting | 40–50        | 240                  | 28–30          | 2006            | Yan et al. 2015                  |
| Xixuan 03     | From natural variation of cassava germplasm ZM92-174 population | High yield, high starch content, stem good to storage | 34.5         | –                    | 29–31          | 2007            | Yan et al. 2015                  |
| Xixuan 04     | From natural variation of cassava germplasm OMR-38-136-1 population | High yield, high starch content, stem germinates quickly and neatly, and had high germination rate, wide adaptability, resistance to pest and disease, tolerance to cold | 46–57        | –                    | 30–31          | 2010            | Yan et al. 2015                  |
| Xixuan 05     | Using cassava variety Xinxuan 048 as material and selected and bred from its variant strain by radiation mutagenesis | High yield, high starch content, no branches | 52–70        | –                    | 29–31          | 2013            | Yan et al. 2015                  |
| Xixuan 06     | Using cassava variety Xinxuan 048 as material and selected and bred from its variant strain by radiation mutagenesis | High yield, high starch content, no branches, tolerance to drought and cold | 50–59        | –                    | 30–31          | 2014            | Yan et al. 2015                  |
| Xixuan 07     | Using cassava variety Xinxuan 048 as material and selected and bred from its variant strain by radiation mutagenesis | High yield, high starch content, no branches. Stem germinates quickly and neatly, and had high germination rate | 53–70        | –                    | 31–32          | 2016            | Unpublished data                 |
| GK 09-26      | SC5 × SC205                                             | High yield, low starch, strong adaptability, tolerance to cold, fertilizer, poor soil, drought weather, pests and diseases | 45–48        | 300                  | 28             | 2014            | Unpublished data                 |
| GK 09-11      | SC5 × SC205                                             | High yield, high starch, strong adaptability | 37.5–45      | –                    | 30–31          | 2015            | Unpublished data                 |
| NZ 199        | Introduced tissue culture seedlings from CIAT            | High yield, high starch content, easy to harvest, low cyanic content | 30–45        | 240–270              | 30             | –               | An et al. 2014                   |
yielding variety but also produces higher starch content with shorter phenotype and XX048 produces high yield, but with lower starch content (unpublished data). After successful field evaluations conducted by CIAT with support of the Nippon Foundation, the CATAS cassava breeding team released six new varieties; SC9, SC10, SC11, SC12, SC13 and SC14 (Chen et al. 2014, 2017a). SC9, an edible variety with yellow flesh and good cooking quality, has been widely planted by smallholder farmers. SC12 and SC13 are mainly planted in Hainan and SC14 is tolerant to PPD. Three other varieties, H1071, ITBB01 and ITBB04, have undergone regional testing in the last five years and ready to be released in the near future. In particular, ITBB04 is a high-yielding variety with desirable plant phenotype (short), erect petioles, plump storage roots suitable for mechanical harvest (Chen et al. 2014, 2017a), and moderate waterlogging tolerance (personal observation).

In Guangxi province, the cassava breeding program released four varieties; GR891, GR911, GR4, and GR6. Among them, GR891 and GR911 have good starch quality suitable for both commercial production and food and have been planted in the northern area of Guangxi province. On the other hand, GR4 has a single stem which is considered as a very good plant type and is planted in the higher latitude regions (unpublished data).

First generation markers, such as simple sequence repeat (SSR), inter-simple sequence repeat (ISSR) and amplified fragment length polymorphism (AFLP), are regularly used to select the qualitative traits, for example, for resistance to CMD and PPD (Nzuki et al. 2017). In addition to Single Nucleotide Polymorphism (SNP) markers, a new simplified re-sequencing technique, called amplified-fragments SNP and methylation (AFSM) approach for genotype profiling was developed in China (Xia et al. 2014). Using this method, 760 cassava lines including 200 landraces from Brazil, 150 accessions from CIAT, 156 collections from China and 254 individuals from a hybridized population of KU50 × SC124, have been genotyped (unpublished data). Large amounts of phenotyping data, collected over a three-year field evaluation across Asia and America, were used to identify whole genome markers for storage root yield, root starch quality, plant and leaf type, and tolerance to cold and drought (unpublished data). In addition, another 350 accessions collected from CIAT, Brazil and Asia during 2013–2018, were also added to the national cassava genebank collection. This collection, with more than 1,000 accessions, has been screened for desirable plant types (i.e., less branching, short height and short duration), tolerance to abiotic and biotic stresses, and high starch content and composition (Zou et al. 2017, unpublished data).

In the last 10 years, stable and highly efficient cassava transgenic techniques without genotype dependence have been developed and used to elucidate gene functions in cassava (Liu et al. 2011). At least four important genes, including two CC-type glutaredoxins (GRXs: MeGRX058, MeGRX785), MeSuSy4, a gene encoding the sucrose-hydrolysing enzyme and MeSOD, superoxide dismutase gene, have been over-expressed and knocked out to reveal the mechanisms of drought and PPD tolerance (unpublished data). Furthermore, silencing granule bound starch synthase II (GBSSII) gene in cassava created a waxy cassava clone with almost 98% amylopectin (Zhao et al. 2011), and overexpression of filamenting temperature-sensitive Z1 (MeFtsZ1) gene enlarged the starch granules of transgenic lines (unpublished data).

Despite the above-mentioned successes of cassava breeding in China, many physiological and agronomical traits are still need to be addressed. Farmer-preferred cultivars adapted to lower temperatures with early maturity (Zou et al. 2017) and high yielding in the regions above 25°N latitude are still need to be developed. Furthermore, commercial varieties need integrated resistant genes for cassava bacterial blight (CBB), green mites and PPD.

India

Cassava was introduced to Kerala state as a food crop from Brazil and slowly spread into the neighbouring states of Tamil Nadu and Andhra Pradesh as an industrial crop (Srinivas 2009). Intensive cassava breeding research started after the establishment of the Central Tuber Crop Research Institute (CTCRI) in 1963. The CTCRI maintains a rich genetic resource comprising of indigenous, exotic, landraces and breeding lines including wild relatives of cassava. In 1996, CIAT and CTCRI collaborated by accepting different combinations of F1 seeds (Abraham et al. 2001).

Early breeding research used extensive inter-varietal crosses between superior varieties and recombinant lines. More recently, the CTCRI’s extensive breeding program, with interspecific hybridization mutation breeding and propagation of cassava from true seeds has developed varieties with high yielding, high dry matter and starch contents, early harvestability, and resistance to pests and diseases. Although most of the released varieties are diploid (Table 5), the triploid cassava is correlated with growth vigor, increased starch content and higher tuber yield (e.g., Sree Harsha, Sreekumari et al. 1999). In addition, heterotic (e.g., Sree Reka and Sree Prabha) varieties have also been developed (Easwari et al. 2000). Sree Harsha is the first triploid cassava variety released with very high yield potential (60 t ha⁻¹) and starch content (38–41%). Two other triploid hybrids viz., Sree Athulya and Sree Apporva, with high extractable starch content (>30%) were released in 2013. Several short duration (5–7 months) varieties viz., Sree Jaya, Sree Vijaya and Vellayani Hrazwa, have also been developed and ideal for planting in paddy fallow in Kerala. On the other hand, H-226 and H-165 are the most popular varieties in the industrial belt of Tamil Nadu. CO-1, Sree Sahya, Sree Visakham, CO-3, H-119, CO (TP-4), Mulluvadai, Kumkumarose and Sree Rekha are also grown in Tamil Nadu.

In 2006, an exotic accession, MNgal with CMD resistance, was released by CTCRI as Sree Padmanabha in Tamil
| Cultivar | Pedigree | Trait of interest | Yield | Reference |
|----------|----------|------------------|-------|-----------|
| H-165 | Manjavella × Accession No. 300 (Brazilian seedling selection) | Conical short roots, drought tolerant | 35–40 | 300–320 | 31 |
| H-166 | Manjavella × Accession No. 300 (Brazilian seedling selection) | Conical short roots, drought tolerant | 35–40 | 300–320 | 31 |
| H-262 | Chadyamangalam Vella × Kalikkalan | Early maturing, tolerant to spider mite and scale insects | 30–35 | 290–310 | 29 |
| H-168 | Chadyamangalam Vella × Kalikkalan | Early maturing, tolerant to spider mite and scale insects | 30–35 | 290–310 | 29 |
| H-294 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-336 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-386 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-340 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-402 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-452 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-501 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-550 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-594 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-646 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-704 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-74 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-349 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-391 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-441 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-494 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-544 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-594 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-646 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-704 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-74 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-349 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-391 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-441 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-494 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-544 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-594 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
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| H-646 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-704 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-74 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-349 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-391 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-441 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-494 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-544 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-594 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-646 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
| H-704 | Selection from indigenous germplasm accession | Conical short roots, drought tolerant | 25–30 | 290–310 | 29 |
remains the principal food crop. Indonesia is the largest industrial use.

Legumes and Tuber Crops Research Institute (ILETRI) are to CMD as well as tolerance to post-harvest deterioration. was released for cultivation in Kerala with higher resistance advancements in the development of CMD-resistant types have been made. Among the CMD-resistant hybrids recently, CIAT-introduced variety Sree Reksha (CR24-4) clones with CMD resistance, including 8S501-2, CR43-2 was bred for low cyanogenic potential, good flesh texture, yellow flesh and harvestability.

From 1982–2016, 12 cassava varieties were released (Table 6), including Adira 1, a yellowish cassava for its β-carotene content (Priadi et al. 2009) with moderate resistant to root rot and Adira 4 is resistance to both root rot and red mite (Sholihin 2011, 2017). In terms of yield potential to ethanol, Litbang UK2 ranked the highest with the yield production of 14,472 litre ha$^{-1}$ which is 20% and 33% higher than Adira 4 and UJ5, respectively (Sholihin et al. 2011, Sholihin 2017).

Philippines
Since 1982, CIAT developed 40,809 hybrid seeds, which were evaluated in the Philippines and the selected elite material was used for further breeding and varietal release (Mariscal et al. 2001). Later, in the 1990s, the Thai-CIAT cassava program collaborated with Philippine Root Crop Research and Training Center (PhilRootcrops) to meet the breeding objectives for cultivating cassava in diverse agro-climatic conditions with high yield, dry matter and starch content, early harvestability, resistance to pests and diseases, and the demands of the processing industries (i.e., starch and alcohol). Since 1982, 48 high-yielding National Seed Industry Council (NSIC)-registered cassava varieties have been released (Mariscal et al. 2001) by PhilRootcrops and local universities.

Cambodia and Laos
Both Cambodia and Lao PDR do not have a cassava breeding program. Most of the cassava varieties grown in this region are from Thailand, Vietnam and China. In Cambodia, farmers in the northwest mainly use varieties from Thailand (KU50/KM94, Huay Bong 60, Rayong 5, Rayong 72, Rayong 60/KM60, Rayong 9, Rayong 11) (Table 2) whereas in the northeast mainly use KM419, a variety from Vietnam (Table 3). These varieties have higher yields and

### Indonesia
Indonesia is one of such few countries where cassava remains the principal food crop. Indonesia is the largest producer of cassava in Asia, producing 44 kg per capita per year or 37.3 kg above the regional average (Howeler et al. 2013). Breeding efforts, therefore, differ from those of other cassava-growing countries, and include non-bitter varieties (i.e., eating varieties) in addition to varieties for industrial use.

Cassava breeding methodologies used by the Indonesian Legumes and Tuber Crops Research Institute (ILETRI) are conventional; involving hybridization, single plant selection, single row selection, single plot selection, preliminary and advanced yield trials, and multi-location trials. In the last few years, the breeding program has incorporated mutation breeding aimed at delivering varieties with high root yield, harvest index and root starch content, non-branching growth habit, good root shape, and tolerance to major pests and diseases [i.e., red mites (Oligonychus biharensis), mealybugs (Phenacoccus manihoti) and root rot (Fusarium sp.)]. In addition, eating varieties are also bred for low cyanogenic potential, good flesh texture, yellow flesh and harvestability.

Table 6. Varieties developed and released in Indonesia since 1978 and their agronomic performance

| Variety       | Traits      | Mean yield (t ha$^{-1}$)* | Starch content (%) | Year of release | References                  |
|---------------|-------------|---------------------------|--------------------|-----------------|----------------------------|
| Adira 1       | Not bitter  | 22                        | 16–18              | 1978            | Balitkabi 2016, Sholihin 2006 |
| Adira 2       | Bitter      | 22                        | n.a.               | 1978            | Balitkabi 2016               |
| Adira 4       | Bitter      | 35                        | 18.5–20.9          | 1987            | Balitkabi 2016, Sholihin 2006, 2011 |
| Malang 1      | Not bitter  | 36.5                      | >20.9              | 1992            | Balitkabi 2016               |
| Malang 2      | Not bitter  | 31.5                      | n.a.               | 1992            | Balitkabi 2016               |
| Darul Hidayah | Not bitter  | n.a.                      | <16                | 1998            | Sholihin 2014                |
| UJ3           | Bitter      | n.a.                      | 20.9               | 2000            | Balitkabi 2016, Sholihin et al. 2015 |
| UJ5           | Bitter      | n.a.                      | 20.5               | 2000            | Balitkabi 2016, Sholihin et al. 2011, 2015 |
| Malang 4      | Bitter      | 39.7                      | 18.5–20.9          | 2001            | Balitkabi 2016, Sholihin 2014 |
| Malang 6      | Bitter      | 36.4                      | 18.5–20.9          | 2001            | Balitkabi 2016, Sholihin 2014 |
| Litbang UK2   | Not bitter  | 42.2                      | 18.5–20.9          | 2012            | Balitkabi 2016, Sholihin et al. 2011 |
| UK1 Agritian  | Not bitter  | 30.2                      | 19.9               | 2016            | Balitkabi 2016               |

* Mean values taken from multi-location trails before varietal release.
starch contents than the two landraces, Damloung Kor and Damloung Mi.

Since 2004, the CIAT Cassava Program in Asia has been working with the National Agriculture and Forestry Research Institute (NAFRI) to evaluate newly improved cassava varieties in Laos. Several varieties including Rayong 5, Rayong 11, Rayong 72 and KU50 from Thailand, SC205 from China, and KM98-1 and KM140 from Vietnam (Table 2) have outperformed local varieties and these varieties have been adopted by Lao farmers (Howeler et al. 2013). Depending on soil fertility, climate and management, the fresh root yields of these varieties range from 12 to 47 t ha$^{-1}$.

## History of cassava agronomy practices in Asia

Cassava yields vary in Asia. Average yields are ~21.5 t ha$^{-1}$ (FAO 2018), with the potential to increase a 2–3 fold with minimal fertilizer inputs and improved management practices (Howeler and Tan 2001). Cassava production varies between sites because of the poor soil fertility, suboptimal weed management and the lack of use of improved varieties. Furthermore, a belief has it that cassava production contributes to soil degradation followed by nutrient depletion and soil erosion. However, research on cassava management has identified that the nutritional requirements (with the exception to potassium) of cassava per unit of dry matter yield are much lower than most crops (Howeler 1991). Cassava is a very efficient user of soil nutrients, thus, the continuous cultivation of cassava without application of appropriate fertilizers depletes the soil nutrients. The slow growing cassava canopy and low planting densities contribute to soil erosion, which not only impacts soil physical properties but also depletes the soil nutrients in topsoil. Thus, CIAT’s cassava agronomy research has focused on narrowing the yield gap and maximizing profits while maintaining soil fertility, which has been made possible with the commitment of the Nippon Foundation (Howeler and Aye 2014).

To maintain healthy soil fertility for cassava production, CIAT has ongoing research collaborations with its national partners in Asia and Australian Centre for International Agricultural Research (ACIAR). Long- and short-term experiments have shown that the response of cassava to NPK fertilizer application varies depending on soil type and fertility status. In general, NPK application had little effect on P levels in fertile soils on cassava root yield. However, without fertilizer application, cassava yields declined over time, which was mainly due to K deficiency. Furthermore, application of biofertilizers (green manure, compost or plant residues) along with chemical fertilizer increased yields (Howeler and Tan 2001, Howeler and Aye 2014).

In short, cassava agronomy research is focused on fertility management and maintenance of erosion control, planting time and harvest to reduce yield gap. In the following sections, we outline the priorities of agronomy research and achievements based on each country.

### Thailand

Improving and maintaining soil fertility with precise fertilizer management along with identifying the optimum conditions for cassava planting in each area is the main focus of agronomic research in Thailand. Therefore, cassava physiology and morphology are studied together with molecular aspects to identify the factors affecting the environmental responses of cassava. The cassava growth model was developed using knowledge and sources made available by the Integrated Breeding Platform (IBP: https://www.integratedbreeding.net/) (Shrestha et al. 2012).

Irrigation is becoming a key factor for good agricultural practices to increase cassava yields in Thailand. An ongoing study demonstrated that surface or subsurface irrigation increased cassava root yield, for example, drip irrigation increased root yields up to 67.5 t ha$^{-1}$ in use of line CMR 43-08-89 which is 1.3-fold fresher root yield than the popular cultivar HB60 grown in a plot experiment. However, not all cassava cultivars are adapted to irrigated conditions since line CMR43-08-89 did not show improvement in starch content, whereas HB60 produced more starch content (30.2%) than CMR43-08-89 (18.7%) (Kittipadakul et al. 2014).

### Vietnam

In general, cassava agronomy practices highly varies based on the regions of Vietnam, topography and financial resources of the growers. Farmers cultivating cassava on sloppy or marginal land generally belongs to low-income group and often provide little to no input for the fertilizers, plant material or irrigation (Kim et al. 2015). Better-off farmers often come with better land and provide significantly more inputs. The top-tier cassava producers are usually rich, well equipped and have large area covering up to hundreds of hectares. These farmers are mostly in Tay Ninh province, the capital of cassava production where the average yield is highest (~30 t/ha) and starch processing plants are most concentrated (over 60 factories). This is the only place where mechanization and irrigation application are the norm. However, appropriate fertilizer application is still one of the major research foci in Vietnam.

Agronomy research in Vietnam has been focused on soil fertility maintenance; response to fertilizer application; intercropping and soil conservation. Numerous long- and short-term experiments have shown that continuous cultivation of monocropped cassava yielded as low as 3 t/ha$^{-1}$ without fertilizer application but increased up to 20 t ha$^{-1}$ with balanced fertilizer (2:1:2 NPK) application (Nguyen et al. 2001). Experiments on soil fertility maintenance demonstrated that most soils used for long-term cassava planting are degraded. For example, cassava cropping lowered pH and total N, P and exchangeable K contents (Nguyen 1998). Intercropping and crop rotation with maize, peanut,
mung bean and black bean improved soil fertility and increased farm income (Nguyen et al. 2001). Furthermore, erosion control experiments indicated that intercropping and contour planting can be effective. No- or minimum tillage was also effective for erosion control.

**China**

Cassava agronomy research in China initially focused on soil fertility maintenance and erosion control. Nitrogen application on crop establishment had the greatest impact on root yield, with potassium and, in some cases, phosphorus is also very important (Howeler and Aye 2014). A soil erosion control experiment demonstrated that contour ridging, intercropping with peanut or planting with vetiver grass (*Chrysopogon zizanioides*) reduced erosion when cassava was grown on sloping land (Jun et al. 2001). Since the 1990s, depending on the interests and capacity of cassava farmers, some farmers have intercropped cassava with other crops, thereby making full use of their land and increasing the economic benefit per unit of land (Lu et al. 2011). In recent years, intercropping of cassava has spread rapidly and is classified into four major models: 1) intercropping with long-duration crops (rubber, betel nut, and fruit trees) at the seedling stage; 2) intercropping with short-duration crops (watermelon, pumpkin, cantaloupe, corn, soybean, peanut, peppers); 3) intercropping with the traditional Chinese medicinal herbs (*Mesona chinensis* and *Andrographis paniculata* (Burm. f.) Nees; and 4) intercropping with edible mushrooms (straw or oyster mushrooms). It is estimated that intercropping accounts for more than 50% of the total cultivated area of cassava in southern regions of China. For intercropping, farmers have improved water and fertilizer management, which not only increases the yield of intercrop fillers but also fresh cassava yields. Of the above intercropping models, fresh cassava yields per unit area have increased from 7.8 to 25.2% when intercropped with watermelon, pumpkin, muskmelon or chieh-qua, and 6.1 to 17.4% when intercropped with peanut or soybean, relative to monocropping cassava (Chen et al. 2017b, Lu et al. 2011). The ranking for the intercropping crops for increasing fresh cassava yield was muskmelon > pumpkin > soybean > watermelon > chieh-qua > peanut (Lu et al. 2011).

**Indonesia**

Cassava production in Indonesia mostly occurs in upland areas that are low in soil nutrients (Sholihin 2006) and susceptible to soil erosion. Furthermore, cassava is grown by smallholder farmers with limited resources. Yields in monocropped cassava without fertilizer application over eight years declined from 25 to 5 t ha\(^{-1}\) (Wargiono et al. 2001). Thus, cassava agronomy activities have focused on soil fertility and cassava productivity. Fertilizer application to improve soil fertility and cassava productivity depend on the variety as well as the soil’s physical and chemical characteristics (Sholihin 2009, Taufiq et al. 2009, 2012).

Results from various soil types and varieties in response to fertilizer application indicated that N and K application could improve cassava productivity by up to 92% in low K soil (Suyamto 1998, Taufiq et al. 2012, Wargiono 2003). Furthermore, the application of organic matter and farmyard manure increased cassava productivity by improving soil physical conditions (bulk density, infiltration rate, etc.) (Sholihin et al. 2010, 2011). Thus, it is recommended that inorganic fertilizer is applied in combination with organic fertilizer to improve cassava production.

The control of soil erosion has also been a focus of agronomy research in Indonesia. Successive cassava cropping and land preparation are two major contributors to soil erosion. Preparing land with minimum tillage to reduce soil erosion had no significant effect on cassava yield (Wargiono et al. 2001). Intercropping can also reduce soil erosion, for example, intercropping cassava with maize, rice or peanut with adequate fertilizer reduced soil erosion for up to 20% compared with monocropped cassava (Wargiono et al. 2001). Planting contour hedgerows with leguminous trees (e.g., *Gliricidia sepium*, *Leucaena leucocephala*) is also a recommended practice for controlling soil erosion.

**Philippines**

In the Philippines, cassava research has focused mainly on maintaining soil fertility and soil conservation practices in collaboration with the CIAT-Asia cassava program. Cassava production in the Philippines increased 1.5 fold from 7.8 t ha\(^{-1}\) to 11.7 t ha\(^{-1}\) over the period of 2003 to 2014 (FAO 2018). While this is encouraging, the national yield remains far below compared to most of the other Asian countries. For example, yields in Thailand, India and Vietnam are currently at 21.8, 34.9 and 18 t ha\(^{-1}\), respectively (FAO 2018). The scarcity of high-yielding varieties and infestation of pests and diseases are the major contributing factors to the lower yields of cassava in the Philippines, but the primary determinant of low yields is due to inadequate crop management practices (fertilizer application and soil fertility management).

Over the years, agronomic research in the Philippines demonstrated that minimum tillage produces better yields than zero tillage. Planting on ridges or mounds in an area susceptible to waterlogging is more preferable. Extensive experimentation has been carried out on the response of NPK at various application levels and combinations at different time period (at planting or 2–3 months after planting) together with the comparisons between organic and inorganic fertilizers (Evangelio 2001). Since most of the cassava are cultivated in the marginal fertile soils, the fertilizer application based on the soil analysis recommendations has produced best results (Villamayor and Destriza 1986). Application of green and animal manures have also increased yields and grass mulching effectively reduced the soil erosion (Evangelio 2001).
India

Agronomy research in India has made tremendous progress over the past years. Extensive research on nutritional requirements, planting methods, cropping systems and long-term fertilizer trials has been undertaken (George et al. 2001). In India, cassava grows in both rainfed and irrigated systems, in which irrigated systems can produce up to 90% more yield than rainfed systems provided with a high dose of NPK (George et al. 2001). Furthermore, irrigated cassava can be planted at any time of the year, whereas April and May are the optimum period for growing cassava in rainfed conditions (Nayar et al. 1985).

Cropping system research demonstrated that short-duration (7 months) cassava could fit into rice-based cropping systems. Intercropping cassava with legumes [ground nuts (Arachis hypogaea) and cowpeas (Vigna unguiculata)] are more remunerative as in situ green manure reduces the N requirement by 50% (George et al. 2001). Furthermore, the use of chemical fertilizer for successive cropping cycles decreased Ca, Mg, Zn and Cu in the soil and lowered pH. Thus, organic manure application to the soil is recommended along with inorganic fertilizer (George et al. 2001).

Cambodia and Laos

In Cambodia, cassava is grown mainly by smallholder farmers with the average land size of 4 ha, but mostly for export as fresh roots and household consumption. Cultivated areas rapidly expanded from 13,000 to 387,636 ha and yield increased from 5.4 t ha$^{-1}$ to 26.3 t ha$^{-1}$ over the period of 1996 to 2016 (FAO 2018), concerning for soil fertility, as fertilizer applications by farmers are not common (Howeler and Aye 2014, Montgomery et al. 2017). The recent pest and disease outbreaks also have become a major constraint for cassava production (Graziosi et al. 2016, Srean 2016).

The collaboration between CIAT and the Agriculture Research and Development Institute (CARDI) has demonstrated ongoing research on fertilizer application and improved variety selection. Along with the emerging threat of pests and diseases (e.g., CMD and CWBD), the major yield constraints for cassava were soil nutrient deficits, short crop duration and weed competition (Sopheap et al. 2012). Farmers commonly grow cassava continuously on the same field without intercropping with other crops or applying organic or inorganic fertilizers (Wenjun et al. 2016).

In Lao PDR, farmers adaptation to improved cassava varieties has increased the cultivation areas and yields from 5,100 ha to 94,726 ha and 13.7 t ha$^{-1}$ to 32.7 t ha$^{-1}$ over the period of 1996 to 2016, respectively (FAO 2018). The considerable opportunities to improve the production and profitability has moved cassava to a ‘cash’ crop for smallholder farmers. However, fertilizer application rates among farmers are still very low.

The Agricultural Research Center (ARC) and National Agriculture and Forestry Research Institute (NAFRI) are in collaboration with CIAT on cassava agronomy. The importance of weed management (Kanthavong et al. 2016) and the positive effects of stake priming (soaking stakes in nutrient solution) on germination and early growth of cassava have been reported (Kanthavong et al. 2014). Pests and diseases have also become a major constraint for cassava production in Laos and a recent survey reported the presence of mealybugs (Phenacoccus sp.) – pink mealybug (P. manihoti) and green mealybug (P. madeirensis) – whiteflies (Bemisia tabaci), red mites (Tetranychus truncatus) and Cassava Witches Broom Disease (CWBD).

High-density DNA screening and large-scale genome sequencing technologies (Bumgarner 2013, Muir et al. 2016) have greatly increased the discovery of single base variation, which can be associated with the change in traits. Recently, initiatives to complete the cassava genetic map have resulted in the incorporation of expressed sequence tags (ESTs) and next-generation sequencing SNPs in a consensus linkage map using the K family (Soto et al. 2015) and consensus 2412-cM map using 22,403 SNP markers, integrating ten biparental maps (ICGMC 2014). This multiple biparental consensus map enabled to anchor 71.9% of the draft genome assembly and 90.7% of the predicted protein-coding genes. Thus, the chromosome-anchored genome sequences will assist in the rapid identification of markers linked to important traits for cassava breeding (ICGMC 2014).

AFLPs and SSR markers have been used on cassava genetic diversity studies and exploitation of gene sequence variation for important traits, such as CMD (Akano et al. 2002) and CBB (Fregene et al. 2003, López et al. 2007, Vásquez and López 2014). These molecular marker technologies have been largely superseded with the rapid identification of a large number of SNP variants through next-generation sequencing (Rabbi et al. 2015, Soto et al. 2015) and subsequent release of the first draft of the cassava genome (Prochnik et al. 2012, UANews 2009, Wang et al. 2014). The recent application of SNPs derived from genotyping by sequence (GBS) identified major quantitative trait loci (QTL) for resistance to cassava brown streak disease (CBSD) developed from a F$_{1}$ cross between a breeding line and an African landrace, Kiroba, identified to CBSD tolerant by breeders (Nzuki et al. 2017), revealing that some of the QTLs associated with CBSD in Kiroba differ from those previously reported and could be a new source of tolerance. In addition to QTL identifications for acceleration of breeding objectives (Ceballos et al. 2015), another important application of markers is to verify the integrity of varieties managed by breeders, seed producers and farmers. A Fluidigm Dynamic Array™ 180 SNP-array (cassava SNPY-array) was recently developed by the CIAT cassava program and used in several studies to identify: 1)
landraces and improved cultigens in farmers’ fields; 2) duplicates in CIAT’s germplasm collection (previously done using SSRs); 3) genetic diversity analysis of germplasm from the littoral and Amazonian regions of Colombia (Floro et al. 2017, Peña-Venegas et al. 2014). This array has also been tested among farmer-grown varieties released in Vietnam to measure the impact of cassava breeding as described above (Le et al. 2019).

Although significant progress in cassava genetics has been made through conventional and marker-assisted breeding (Ceballos et al. 2015), new regional challenges and the effect of impending climate change (Ghini et al. 2011), on pest and disease outbreaks such as SLCMV (Minato et al. 2019), presents additional challenges to the breeders. From an industrial viewpoint, development of value-added cassava with improved starch quality and new starch type (Bechoff et al. 2018) are always in high demand. The recent emergence of genome-editing technologies such as CRISPR/Cas9 system has been a great milestone (Hummel et al. 2018, Odipo et al. 2017) in crop genetic improvement such as disease resistance (Gomez et al. 2018). Bull et al. (2018) demonstrated that mutagenesis of two genes, PROTEIN TARGETING TO STARCH (PTST1) and GRANULE BOUND STARCH SYNTHESE (GBSS), involved in amylopectin biosynthesis could reduce or eliminate amylose content in root starch. Interestingly, most of the pstl lines produced starch with an average of 13.3% amylose compared to 18.5% in the wild type. Unlike some of the gbss mutant lines, none of the pstl lines produced amylose-free (waxy) starch. This indicates that genome-editing technology can identify interesting lines containing a spectrum of different amylose contents for the cassava starch industry and provide new insights into the role of these genes in cassava starch biosynthesis.

Cassava encodes five eukaryotic translation initiation factor 4E (eIF4E) isoforms, including the novel cap-binding protein-1 (nCBP-1) that interacts with cassava brown streak virus genome-linked protein (Vpg) to cause CBSD in Africa. Generations of ncbp-1, ncbp-2, and ncbp-1/ncbp-2 cassava mutants by CRISPR/Cas9-mediated genome editing demonstrated reduced severity against CBSD and incidence of storage root necrosis, as well as delayed and diminished aerial symptoms (Gomez et al. 2018). Thus, CRISPR/Cas9 genome editing is advantageous in simultaneously targeting multiple genes relative to earlier genetic engineering techniques such as RNA interference (RNAi) (Blow 2008).

To accelerate cassava breeding in Asia through the application of new breeding technologies (Germini et al. 2018), the International Laboratory for Cassava Molecular Breeding (ILCMB) was established in 2012 between a collaborative framework of AGI under the Vietnamese Academy of Agricultural Sciences (VAAS) in Hanoi, Vietnam and CIAT with RIKEN. At ILCMB, efforts to establish genome-editing technologies in farmer-preferred varieties are underway. The application of this technology in cassava has indicated the importance of establishing a sustainable induction system of friable embryogenic callus (FEC) in the preferred varieties including KU50 (Utsumi et al. 2017), even though regeneration of whole cassava plants from transformed FEC was already reported in the mid-1990’s (Li et al. 1996). Recently, an in planta genome-editing procedure was established for wheat cultivars using shoot apical meristems (SAMs) that are target cells for biolistic delivery (Hamada et al. 2018). This methodology could be an alternative for developing genome-edited crops such as cassava, which are not easy to transform by conventional procedures.

Crop phenotyping through disruptive technologies such as the Internet of Things (IoT) and artificial intelligence (AI) have rapidly progressed (Araus et al. 2018, Tattaris et al. 2016). The recent developments in deep learning technologies of AI, together with high-performance computing have been successfully applied in different research fields to extract meaningful features from the collected digital data (Ghosal et al. 2018, Liakos et al. 2018). A novel tool for cassava disease detection was reported using deep learning models to identify three diseases and two types of pest damage, with an overall accuracy of 93% for non-trained data, making plant disease detection robust, cost-effective and scalable (Ramacharan et al. 2017).

CIAT’s phenomics platform is being established to facilitate trait identification and its validation for breeding and agronomy research by integrating ground truth and remote sensing data. Fig. 1 shows the platform integrating ground truth and remote sensing data sets captured by unmanned aerial vehicles (UAV) and satellite imaging technologies using freely available, medium-resolution satellite imagery (e.g., Sentinel 2) with which the land cover and crop health status are assessed on a large scale (data not published).

Apart from aboveground monitoring, technologies are also available to predict storage root growth and development. One such novel method currently being explored by CIAT, in collaboration with Texas A&M University, is the use of ground-penetrating radar (GPR) to predict cassava root biomass. Preliminary work has demonstrated that GPR can explicate root and tuber characteristics such as early bulking and volumetric dimensions (Delgado et al. 2017), which will be very useful for selecting early maturing cassava cultivars in breeding program. Thus, disruptive technologies such as sensors, UAV, satellites and AI will have a huge impact on agricultural research to identify the best-performing lines in early breeding cycles of large breeding populations (King 2017, Liakos et al. 2018).

**Regionally coordinated research and development in Asia**

The coordinated efforts of CIAT with the national program in Asia has increased cassava productivity from 13.0 t ha⁻¹ in 1996 to 21.3 t ha⁻¹ in 2016 through the adoption of improved varieties (Labarta et al. 2017) and better agronomic...
practices (FAO 2018). To further strengthen regional co-operation and coordinated research activities in cassava breeding, the Asia Cassava Breeders Network (ACB-Net: http://www.acb-net.com/) was established in 2015. This group aims to bring together conventional breeding programs and molecular breeding laboratories, and forge public-private partnerships in variety development and evaluation. The CGIAR research program on Roots, Tubers and Bananas (RTB) is a protagonist in the regional cooperation on cassava improvement. Research activities for short-duration crops such as potato, sweet potato and yam have the potential to incorporate cassava production systems to improve farmer’s income in Asia.

In Asia, cassava seed (stem cuttings) systems distribution generally involves farmer to farmer channel and in many cases, seed can travel several hundred kilometres, crossing country borders. This informal distribution of the seed system is a major cause for the spread of cassava diseases like SLCMV and CWBD (Graziosi et al. 2016), threatening its productivity. SLCMV was first reported in a province of Cambodia in 2016 (Wang et al. 2016), but now been reported in four other provinces of Cambodia and one province in Vietnam (Uke et al. 2018). Thus, regionally coordinated research on seed systems, pest and disease control, and capacity-building efforts should be launched to ensure the profitability and sustainability of cassava production systems in Asia (Graziosi et al. 2016). Towards archiving the regional goals, the Global Cassava Partnership for the 21st Century (GCP21), a not-for-profit international alliance of 45 organizations, organized a stakeholder meeting in September 2018 to design a plan of action to prevent the spread of cassava mosaic disease in Southeast Asia.

**Conclusions**

Cassava research and development has been successful in Asia in the past half-century. Breeding high-yielding varieties with improved agronomic practices mobilized strong partnerships with numerous stakeholders. Breeding programs with industry targeted commercial traits foster sub-sector development. Different breeding technologies employing traditional and modern techniques such as marker development, genome editing contributed to the development of new varieties.

Agronomic research initially focused on the introduction of diverse germplasm to the region and later reached milestones with improved agronomical practices focusing on yield attributes and crop management practices such as fertilizer inputs, weed management, sowing methods and soil erosion control. In the coming years, application of disrupting technologies such as IoT and AI combined with multisensors (Ferrández-Pastor et al. 2016, Jayaraman et al. 2016, Tzounis et al. 2017), will allow farmers and vital players in agricultural field to retrieve crop variable and productivity leading to sustainable development of cassava production.

**Author Contribution Statement**

Al Imran Malik and Manabu Ishitani designed the structure of the review and compile the draft and co-lead the project. Individual country sections were drafted as follows, Thailand: Pasajee Kongsil, Piya Kittipadakul Pornsak Aiemnaka and Suwaluk Amawan; Vietnam: Vũ Anh Nguyễn, Hữu Hỷ Nguyễn Trọng Hiển Nguyễn, Hai Anh Nguyễn, Văn Đồng Nguyễn and Lê Huy Hàm; China: Wenjun Ou, Cheng Lu, Songbi Chen and Wenquan Wang;
Indonesia: Sholihin; Cambodia: Pao Srean and Sopharith Sok; India: MN Sheela; Laos: Laothao Youbee. Furthermore, Luis Augusto Becerra López-Lalvalle contributed to the molecular breeding section, Yoshinori Utsumi, Motoaki Seki and Hiroki Tokunaga contributed to new breeding technique section. Hernan Ceballos contributed to the breeding section, Michael Selvaraj Gomez contributed the digital agriculture section, and Ricardo Labarta contributed to the sections on varietal dissemination.

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