

# Vietnamese cassava varieties progression across 50 years

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## **Abstract:**

Vietnamese cassava varieties constitute the fundamental and pivotal element in the sustainable development programme for cassava. This article aims to encapsulate the advancements made over nearly five decades in breeding and enhancing Vietnamese cassava varieties. It delineates the suitable cassava variety structures for each period and ecological region. The selection of cassava varieties exhibiting high starch yield and disease resistance, coupled with the establishment of a suitable and efficient cassava cultivation model, exemplified by 10T for Vietnamese cassava varieties KM568, KM539, KM537, KM569, and KM94, stands as a cornerstone for sustaining cassava development over the years. Presently, we advocate for farmers to cultivate promising cassava varieties such as KM568 or KM539 (an enhanced version of the International Center for Tropical Agriculture (CIAT) cassava variety C39, refined through multiple breeding cycles from 2004 onwards), KM537, KM569, or HN1 (originally known as TMEB419), alongside popular cassava varieties: KM440, KM419, KM94, KM7, STB1, KM414, KM98-7, KM140, KM98-5, KM98-1. We have conducted Distinctness, Uniformity, and Stability (DUS) and Value for Cultivation and Use (VCU) tests, showcasing outstanding cassava varieties in large-scale farming, thereby providing compelling evidence for the prudent conservation and sustainable development of cassava. Vietnamese cassava progression (1975 to date) has traversed six stages, with five waves of restructuring cassava varieties, aligning with target orientations, farming conditions, and market demands, culminating in 16 popular cassava varieties and four promising cassava varieties KM568, KM539, KM537, and KM569.

**Keywords:** Cassava varieties; Distinctness, Uniformity, and Stability (DUS) and Value for Cultivation and Use (VCU); progression; Vietnam.

**Classification number:** 3.1

## **1. Introduction**

Cassava (*Manihot esculenta* Crantz) emerges as a pivotal crop in the 21<sup>st</sup> century, serving purposes ranging from food and animal feed to starch processing and biofuel production worldwide. In Vietnam, cassava, alongside rice and corn, occupies a position of primacy in research and development according to the vision of the Government and the Ministry of Agriculture and Rural Development (MARD). This comprehensive article serves as a sequel to the work presented by K. Hoang, et al. (2018) [1] on “Conservation and sustainable development of Vietnamese cassava”.

The aim of this review study is to amalgamate the findings of cassava breeding spanning the past five decades, elucidating the lineage of popular cassava varieties alongside promising ones in the ongoing development of Vietnamese cassava varieties from 1975 to the present. In response to requests from CIAT, the MARD, and Phu Yen province, this article encompasses six key sections: 1. Introduction; 2. The current status of cassava in Vietnam; 3. The process of breeding and developing Vietnamese cassava varieties (1975 to date); 4. Promising cassava varieties for the cassava program in Vietnam; 5. Conservation and sustainable development of Vietnamese cassava; and 6. Conclusions. Addressing

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these requests, the article integrates the aforementioned sections to provide further clarity: Identifying the significance of cassava, the current state of cassava cultivation in Vietnam, the history of breeding, breeding methodologies, main cassava varieties with their primary characteristics, recent advancements in cassava breeding, and the latest findings and references for each subgroup.

The sustained effort over nearly five decades has propelled significant advancements in cassava breeding, facilitated by the Vietnam National Cassava Program (VNCP) that connects various academic institutions such as the Nong Lam University - Ho Chi Minh City (NLU), University of Agriculture and Forestry, Hue University (HUAF), Thai Nguyen University of Agriculture and Forestry (TNAF), Hung Loc Agricultural Research Center (HARC), Root Crop Research and Development Centre (RCRDC), Tay Nguyen University (TNU), the One Commune One Product (OCOP) network of provinces, notably Phu Yen provinces, and the more recently established International Laboratory for Cassava Molecular Breeding (ILCMB), a collaborative effort between CIAT, RIKEN, and the Vietnamese Institute of Agricultural Genetics.

Vietnam's cassava production has witnessed remarkable progress in productivity owing to: i) increased breeding efforts and the adoption of new varieties and agricultural techniques; ii) progressively supportive governmental policies; and iii) sustained backing from international organisations, particularly the CIAT, and more recently, Australian Centre for International Agricultural Research (ACIAR).

## 2. The current status of cassava in Vietnam

Vietnamese cassava stands as a remarkable success story today [2]. The current cultivation of cassava in Vietnam spans an area exceeding half a million hectares annually, with exported cassava products valued between 0.8 and 1.2 billion USD [3]. Nationally, cassava has emerged as a significant export crop, offering avenues for increased income, livelihood enhancement, and improved living standards for millions of smallholder farmers.

The yield and total output of cassava in Vietnam have seen significant increases, soaring from 8.35 tons/ha and 1.98 million tons in 2000 to 17.90 tons/ha and 9.74 million tons in 2013, marking a doubling in yield and a fivefold increase in total production [4].

The cassava revolution in Vietnam serves as a distinguished model in Asia and globally, characterised by the selection of high-starch-yielding cassava varieties, widespread adoption of sustainable farming practices, and advancements in production, post-harvest processing, value chain enhancement, and market expansion [5].

The pivotal role of selecting Vietnamese cassava varieties cannot be overstated. Millions of Vietnamese farming households have reaped the benefits of improved cassava varieties, experiencing heightened productivity, increased profits, and enhanced livelihoods. The project on the “Conservation and sustainable development of cassava in Vietnam” has yielded notable success, substantiated by testing and demonstration results in Tay Ninh, Phu Yen, Dak Lak, and Dong Nai provinces, where farmers employing superior cassava varieties and appropriate intensive farming techniques have witnessed a surge in cassava yield from 8.5 tons/ha in 2000 to over 36.0 tons/ha on a large scale today, representing a substantial increase in yield and total output. The history of cassava breeding in Vietnam, methods of cassava multiplication, exchanges of cassava genetic resources between VNCP & CIAT, and the achievements and lessons from Vietnam's cassava revolution are encapsulated in the article “Conservation and sustainable development of cassava in Vietnam” by K. Hoang, et al. (2018) [1]. The collaborative efforts of VNCP, Phu Yen province, NLU, and the broader connected community bode well for the future of developing Vietnamese cassava varieties.

The surge in productivity, output, and economic efficiency of Vietnamese cassava has coincided with the emergence and spread of cassava witches' broom disease caused by *Phytoplasma* sp. (CWBD) on heavily infected cassava variety KM94 and Sri Lanka Cassava Mosaic virus disease on heavily infected cassava variety HLS11, inflicting serious damage in 17 provinces [6]. Improving and upgrading the most popular cassava varieties with high starch yield and resistance to pests and diseases stands as an effective solution to sustain and enhance cassava production [7].

In 2022, cassava production in Vietnam encompassed an area of 528.0 thousand hectares, yielding an average of 20.3 tons/ha of fresh roots, resulting in a total output of 10.7 million tons [8]. The five primary cassava-growing regions of Vietnam are: 1) The Central Highlands region, comprising 172.5 thousand hectares of cassava, accounting for 32.7% of the total cassava

area, with focal points in Gia Lai (81.0 thousand hectares), Dak Lak (45.0 thousand hectares), and Kon Tum (38.8 thousand hectares); 2) The South Central Coast region, encompassing 102.0 thousand hectares of cassava, accounting for 19.3% of the total cassava area, with major concentrations in Phu Yen (29.5 thousand hectares), Binh Thuan (28.0 thousand hectares), Quang Ngai (17.0 thousand hectares), and Quang Nam (10.0 thousand hectares); 3) The Southeast region, hosting 92.8 thousand hectares of cassava, accounting for 17.6% of the total cassava area, with significant presence in Tay Ninh (59.0 thousand hectares) and Dong Nai (17.0 thousand hectares); 4) The Northern midlands and mountains, with 99.3 thousand hectares of cassava, accounting for 18.9% of the total cassava area, scattered across mountainous provinces including Son La, Yen Bai, and Hoa Binh; and 5) The North Central region, with 53.0 thousand hectares of cassava, comprising 10% of the total cassava area, predominantly concentrated in Nghe An, Thanh Hoa, and Quang Tri (12-13 thousand hectares per province) [9].

Presently, selecting cassava varieties with high starch yield and disease resistance and implementing a suitable and effective cassava cultivation model like the 10T model for Vietnamese cassava varieties such as KM568, KM539, KM537, KM569, and KM94 remain crucial for maintenance and development. Farmers now prefer disease-resistant promising cassava varieties like KM568, KM539 (an excellent improved version of the

imported CIAT cassava variety C39), KM537, KM569, and HN1 (originally known as TMEB419), alongside popular cassava varieties such as KM440, KM419, KM94, KM7, STB1, KM414, KM98-7, KM140, KM98-5, and KM98-1. The remarkable outcomes of VCU and DUS tests and large-scale demonstrations in farmers' fields serve as compelling evidence for the sustainable development of the cassava programme. Notably, the enhancement and improvement of cassava varieties KM419, KM440, and KM539 in Phu Yen province reflect significant achievements [10, 11]. The availability of superior cassava varieties and the '10T cassava farming techniques model' have paved the way for the application and expansion of the 'Sustainable agricultural and rural development strategy for the period 2021-2030' [12], alongside national target programmes and the VAEM & TNU VSTA initiative.

### 3. The process of breeding and developing Vietnamese cassava varieties (1975 to date)

The evolution of Vietnamese cassava varieties (1975 - present) has traversed six stages, marked by five waves of structural transformation in cassava varieties, aligning with target orientations amidst diverse farming conditions and market demands. This progression entails the cultivation of 16 popular cassava varieties and 4 elite promising varieties: KM568, KM569, KM539, and KM569 (refer to Fig. 1 and Table 1).

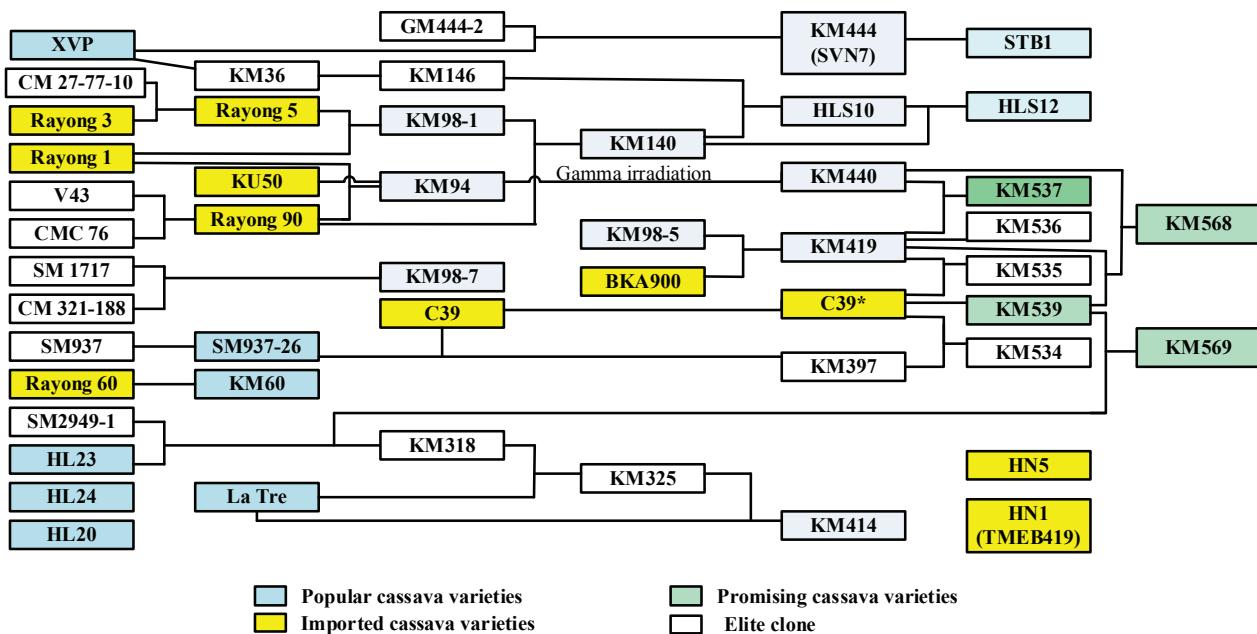


Fig. 1. Flowchart illustrating the progression of Vietnamese cassava varieties from 1975 to the present.

*Period 1975-1990:* The focus during this phase was on collecting and conserving genetic resources of root crops, selecting high-yield, quality cassava varieties suitable for both food and animal feed purposes. Notably, the HL23 cassava variety emerged as a pivotal production staple. Cassava cultivation extended across all ecological regions of the country except for the rice-growing lowlands in the Mekong delta and Red river delta. Productivity during this era ranged from 6 to 8 tons/ha [13]. Popular varieties included Gon, H34, and Xanh Vinh Phu before 1985, transitioning to HL23, HL20, and HL24 between 1986 and 1990. These selections, predominantly from the Hung Loc Agricultural Experimental Research Center, covered an area of 70,000-80,000 hectares, particularly in southern provinces, boasting yields exceeding 16.5 tons/ha [14].

The HL23 variety, renowned for its delectable taste, exhibited a yield of 29.8 tons/ha and starch content of 25.3% [15]. This period also marked the inception of the strategy for the “Conservation and sustainable development of cassava in Vietnam” [1, 16, 17], led by the VNCP connecting HARC (under Institute of Agricultural Science for Southern Vietnam), Department of Agronomy, NLU, RCRDC (under Vietnam Academy of Agricultural Sciences (VAAS) with international organizations such as CIAT, IDRC, Viet Nga, and Viet Tiep aimed at collecting, evaluating, using and preserving genetic resources of tubers and biodiversity [18, 19]. Similarly, VNCP collaborated with VEDAN and Ajinomoto to undertake a research and development program for cassava production, processing, and consumption markets.

*Period 1991-2000:* Characterised by an in-depth exploration of cassava production, processing, and market dynamics, this phase witnessed the selection of varieties with high starch yield and broad adaptability, tailored for starch and cassava chip export. Key varieties during this period included KM94, KM98-1, and SM937-26. The collaboration between VNCP and CIAT since 1988 brought about a notable transformation in the Vietnamese cassava program, leading to a robust national initiative for production, processing, and market expansion, as underscored in the Vietnam Cassava Strategy Workshop in Hanoi [20].

Some cassava varieties imported from CIAT Thailand, such as Rayong 60 and KU50, exhibited high starch yield through the cassava variety evaluation network. Further selection in Vietnam resulted in KM60 and KM94, respectively, which received certification from MARD in 1992 and 1995 [21-24]. Additionally, the selection and development of cassava variety SM937-26, derived from hybrid cassava seeds imported from CIAT Colombia and CIAT Thailand, occurred during this period [21, 22, 25-27].

*Cassava variety KM94 (KU50)* boasted a fresh tuber yield of 33.0 tons/ha with a starch content of 28.7%, exhibiting a wide adaptability spectrum suitable for Vietnam’s cassava starch processing industry. KM94 was complemented by varieties KM98-1 and SM937-26.

*Cassava variety KM98-1*, with its high starch yield, was a versatile variety with a short growth duration, suitable for fresh consumption. It served as a valuable supplement and replacement for cassava varieties HL23, HL24, HL20, and Xanh Vinh Phu, which were renowned for their delicious taste and suitability for both fresh consumption and animal feed during this period.

*Cassava variety SM937-26*, characterised by high dry cassava chip yield, starch yield, drought tolerance, and disease resistance, underwent continuous improvement and upgrading from this period onwards. It eventually evolved into cassava variety KM7, an elite version of KM505, KM397, and KM937-26 x BKA900. The breeding and selection of this elite line from cassava crosses were conducted in Vietnam, following the method of selecting cassava lines from double haploid hybrid using CIAT technique [28-32]. Backcrossing, selective breeding, and sexual hybridisation were continuously implemented, resulting in cassava variety KM534 (KM397 x KM539). The results of multi-site testing, pilot model building, multiplication, and dissemination of cassava variety KM937-26 over many seasons were documented by numerous authors [33-37].

*Cassava variety KM98-1:* The method of pedigree selection was applied to develop KM98-1 from the hybrid of Rayong 1 x Rayong 5 in Vietnam [38-40]. The KM98-1 shares the same genetic pedigree as the widely popular Rayong 72 cassava variety in Thailand. In Cambodia, KM98-1, also known as cassava variety 81, thrived and showed promising results in Vietnam, Laos, and Myanmar. Another improved version of KM98-1, known as NA1 cassava variety in Vietnam, emerged

from the cooperation between Vietnam, Laos, Cambodia in transferring cassava seed technology advances and CIAT's Asian cassava program. At the 2000 Technical Innovation Contest, KM98-1, together with KM98-5, received the gold medal for Vietnamese brand, awarded by the People's Committee of Can Tho city and the Organising Committee of the Can Tho International Fair [1].

*Period 2001-2010:* Vietnam witnessed the emergence of a second wave of breakthrough cassava varieties, characterised by the crossing and selection to develop varieties with high starch yield, short growth duration, and suitability for diverse ecological regions. The primary aim was to meet the demands of starch and cassava chip production. Prominent varieties during this period included KM94, KM140, KM98-5, KM98-7, KM98-1, and KM397 (an improved version of SM937-26). Supported by the MARD from 2001 to 2005, the VNCP led a project on the development of cassava varieties. This initiative, chaired by the Institute of Agricultural Science for Southern Vietnam, closely collaborated with the CIAT Nippon project, VEDAN company, and cassava processing factories. The project's primary objective was to propagate key cassava varieties for starch and cassava chip production and distribute them to cassava-growing provinces nationwide.

A summary of cassava achievements and the three main lessons learned 6M, 10T, and 1F, focusing on the conservation and sustainable development of cassava in Vietnam, highlighted the preservation of rare genetic resources and the introduction and development of cassava lines from target-oriented hybrids. These efforts linked Vietnam's agricultural research, extension, and teaching system with a network of farmers, processors, consumers, and management businesses, facilitating comprehensive development [25, 26, 41]. The breakthrough achievements of this period included the selection and development of cassava varieties with an ideal plant shape, compact canopy, few branches, high harvest index, increased planting density, and superior fresh tuber yield and starch content. These varieties exhibited a shorter growth duration compared to the KM94 cassava variety, making them suitable for various ecological zones. Consequently, Vietnamese cassava varieties boasted super starchy tubers, compact canopies, short growth durations, and enhanced disease resistance [42].

In the northern region, 70-90% of farmers cultivated popular cassava varieties such as KM94, KM98-7, La Tre, KM95-3, and Xanh Vinh Phu during this period. These varieties were favoured for their high starch yield and versatility, making them suitable for local farming conditions. Farmers preferred readily available varieties for self-multiplication [43-45].

In the central region, 80-100% of farmers grew popular cassava varieties like KM94, KM140, KM98-5, KM98-1, and SM937-26 due to their high starch yield. Cassava variety KM98-1 was identified as multi-purpose, possessing high starch yield, low HCN content, and suitability for both industrial and human consumption [46-49].

In the southern and central highlands, 80-100% of farmers cultivated the main commercial cassava varieties, including KM94, KM140, KM98-5, KM98-1, and SM937-26. Among these, KM140 and KM98-5 were particularly popular during this period [50-53].

Cassava variety KM94 demonstrated widespread adaptability as a result of the "Developing cassava varieties" project supported by MARD. By 2010, it covered 75.5% of the nationwide cassava area. Following KM94 were KM140, KM98-5, KM98-1, SM937-26, KM98-7, HL23, and Xanh Vinh Phu, accounting for 5.40, 4.50, 3.24, 2.70, 1.44, 1.08, 2.70, and 3.40% of the total cassava area, respectively [54].

*KM140, KM98-7, KM98-5, KM98-1, SM937-26, and KM94*, the main cassava varieties, were widely adopted by numerous cassava producers, processors, and consumers. The KM140 cassava variety, renowned for its high starch yield, clinched the first prize at the Vifotec National Technical Innovation Contest, Government of Vietnam 2010, held at the Hanoi Opera House on January 19, 2010 [51, 55].

*Period 2011-2015:* Vietnamese cassava varieties entered a third-wave breakthrough, focusing on research and development for starch and biofuel production [56]. Efforts centred on selecting and transferring cassava varieties with high starch yield, ideal canopy shapes, resistance to major pests and diseases, and suitability for diverse farming conditions. However, this period also witnessed the emergence and spread of various diseases, such as cassava witches' broom disease (CWBD) caused by *Phytoplasma* in 2009 and caused serious damage to cassava variety KM94 in Quang Ngai [57]. In 2011,

Vietnamese cassava infected, cassava bacterial blight (CBB) in 2011, red spiders and pink mealy bugs in 2013, and cassava mosaic disease (CMD) in 2017. The structure of Vietnamese cassava varieties suitable for this period was KM419, KM94, KM440, KM140, KM397 (=KM505), KM98-5, KM98-1, KM98-7, KM444 (STB1), KM414 (KM325 x La Tre).

During this period, the primary cassava variety KM419 (BKA900 x KM98-5) and KM440 (mutant KM94) integrated a super starch gene and exhibited resistance to cassava bacterial blight disease (CBB), cassava witches' broom disease (CWBD), and were less susceptible to red spider mites, pink mealy bugs, and tuber rot disease. They boasted a compact canopy, few branches, and produced uniform and aesthetically pleasing tubers. Consequently, numerous proficient farmers within the VNCP network swiftly propagated these varieties, leading to a rapid transformation in the cassava variety structure in southern provinces [1, 58-61]. KM419, the primary cassava variety, and the popular KM440 accounted for nearly 85% of the cassava cultivation area in Phu Yen province. This resulted in the average cassava yield increasing from 17 tons/ha in 2016 to over 23.5 tons/ha in 2018, contributing more than 293.25 billion VND to the province's economy [62].

Cassava varieties KM101, HLS10, HLS11, HLS12, KM21-12, and Sa06 were imported, selected, and introduced into production concurrently during this phase [63-66]. According to K.C. Tran (2012) [50], three cassava varieties, namely KM140, KM98-5, and KM94, had become the primary cassava varieties in the Southeast and Central Highlands ecological regions. Subsequently, the VNCP initiated a state-level project to evaluate the most promising national cassava varieties across ecological regions throughout the country [67, 68]). The findings identified the most prominent cassava varieties for various regions, including 1) Northern midland and mountainous regions: KM444 (also known as HL2004-28 or SVN7); KM414 (also known as HL2004-32 or SVN8); KM419 (also known as SVN5); 2) North Central region: KM444, KM419, KM414; 3) South Central region: KM444, OMR35-8 (also known as SVN9); GM155-7 (SVN10); 4) Southeast region includes KM419, KM444, KM414. KM419, in particular, was widely embraced by farmers due to its consistently high yield, excellent pest resistance, short growth duration, and ideal plant shape [1, 58].

*Period 2016-2020:* Marked a significant breakthrough in Vietnamese cassava varieties, characterised by the selection of varieties with high starch yield, resistance to major pests and diseases, and suitability for cultivation in diverse ecological regions. The cassava revolution in Vietnam gained international recognition at the Global Cassava Conference in Nanning, China. Five new Vietnamese cassava varieties were unveiled at this conference: KM419, KM440, KM444, KM414, and KM397 [5, 69]. However, the emergence of cassava leaf mosaic virus disease (CMD) in Tay Ninh in May 2017 led to a crisis affecting 17 provinces in the Southeast, South Central Coast, and North Central regions [6]. Following the CMD outbreak, popular cassava varieties for adaptive production included KM440, KM419, KM94, KM140, KM98-5, KM7 (also known as KM505 or KM397 or improved SM937-26), STB1 (KM444), KM414 (KM325 x La Tre), KM98-7, KM98-1, and HN1. According to K. Hoang, et al. (2018) [1], H.H. Le, et al. (2016) [5], and M.T.T. Nguyen (2017) [70], the five new cassava varieties KM419, KM440, KM444, KM397, and KM414 showed the most promise among Vietnamese cassava varieties during this period. Notably, KM419 emerged as the primary cassava variety widely cultivated in provinces such as Tay Ninh, Dong Nai, Dak Lak, and Phu Yen.

*Cassava variety KM414,* originating from testing cassava variety KM101, demonstrated high yield and resistance to some pests and diseases, particularly suited to the Southeast and Central Highlands regions [71]. However, it exhibited the drawback of yellow flesh and slight susceptibility to cassava brown leaf spot disease, bacterial blight of cassava, and red spider mites. KM101, initially named CMR 29-56-101 and imported from Thailand. According to K. Hoang, et al. (2006b) [26], KM101 cassava variety was imported from 3020 + 1982 cassava seeds from CIAT Thailand (import ticket number No. 28885), and underwent breeding by the NLU research team. It was crossed with La Tre to create KM325, later backcrossed to produce KM414 with white flesh, albeit with some susceptibility to diseases, alongside the widely adapted KM98-7 variety in the North (Fig. 1).

*Cassava variety STB1:* Evaluation results by T.D. Pham, et al. (2019) [72] highlighted STB1's high yield potential, ranging from 39.0 to 48.9 tons/ha, with increased productivity compared to the control variety KM94. Starch content in STB1 reached from 26.01% to

29.82%, making it highly regarded locally for raw material production in cassava factories. However, preferences varied regionally, with STB1 and KM7 favoured in the South-Central cassava region [73, 74], while STB1 and KM414 were preferred in the North Central Coast and Northern midland mountain areas [67, 68].

*Period 2021 - present:* The Vietnamese cassava variety programme has achieved a breakthrough in the fifth wave, focusing on selecting the main commercial cassava varieties in Vietnam to attain high starch yield, resistance to major pests and diseases, and an ideal cassava plant shape suitable for diverse ecological regions. T.T.K. Nguyen, et al. (2021) [75] highlight the significance of developing cassava varieties resistant to viruses as a key strategy in controlling CMD. The study suggests that resistant varieties can be developed using genetic technologies such as RNAi and gene editing, or by utilising naturally resistant gene sources, with the latter being deemed the most promising solution. Meanwhile, V.A. Nguyen, et al. (2021) [76] published descriptions and identified some popular cassava varieties in Vietnam. In another study, A.N. Le, et al. (2021) [77] determined the biological characteristics of the whitefly (*Bemisia tabaci*) on the four cassava cultivars KM419, H34, KM98-7 and KM94 under laboratory conditions at 30°C and 70% relative humidity.

*Cassava variety HNI (TMEB419)* gained attention at the Conference on the current status and development orientation of cassava in Vietnam in October 2023. According to X. Zhang, et al. (2023) [78], organisations including AGI, CIAT, JICA, and FAO agreed to prioritise the rapid multiplication of six CMD-resistant cassava varieties, including HN1, HN3, HN5, HN36, HN80, and HN97. Originating from TMEB419, HN1 is regarded as the best-imported cassava variety in the CMD-resistant cassava variety source, boasting a standard CMD-resistant disease score level of 1, a fresh tuber yield of 42.5 tons/ha, and a starch content of 27.5%. However, it exhibits lower adaptability compared to common cassava varieties, along with a slightly lower starch content and taller stature [79].

*Cassava varieties Sa06, 13Sa05 and BK* have shown promise in Northern Vietnam and Nghe An province. According to H.T.T. Pham, et al. (2017, 2018, 2021) [80-82], Sa06 demonstrated high quality after selection

and development efforts, while 13Sa05 and BK offer short growth durations and high yields, suitable for early harvesting to avoid floods.

*Cassava variety HL S12*, H.H. Nguyen, et al. (2021) [83] selected and tested cassava variety HL-S12 originating from the cross combination HL-S10 × KM140 and evaluated this variety at Hung Loc Center from 2014 to 2021. The results showed that HL-S12 was quite resistant to cassava witches' broom disease, red spider, and mosaic leaf disease. Productivity varied from 36.02-42.34 tons/ha; starch content reached 26.1-27.1%, starch yield ranged from 9.42-12.64 tons/ha, which is an increase of 7.5-13.5% compared to control (KM140) and by 4.5-13.4% compared to KM94 [83]. Large-scale testing of cassava variety HL-S12 from 2019 to 2020 in the Southeast and Central Highlands regions demonstrated a 2-year yield from 34.6-47.7 tons/ha and selling price ranges from 1,900-2,200 VND/kg depending on locality. Profits reached from 33.4-72.5 million VND/ha, an increase of 47-134% compared to the control variety.

*Cassava variety KM7 and KM140:* According to P.T. Nguyen (2021) [74], the development of technical measures for cultivating high-yield cassava varieties in Khanh Vinh and Khanh Hoa identified two cassava varieties SM937-26 and KM140 as two economically effective cassava varieties, suitable for Khanh Hoa area. Fresh tuber yield of the cassava variety SM937-26 (New name as KM7) was 43.1-45.7 tons/ha, 27.3-50.7% higher than the control KM94, with starch content of 26.2-27.5%. This variety produced a starch yield ranging from 11.3-12.6 tons/ha and demonstrated good lodging resistance and drought tolerance, with slight susceptibility to cassava witches' broom disease. Cassava variety KM140 had a yield of 43.0-47.2 tons/ha, 31.5-50.3% higher than the control KM94, a starch content 25.5-26.1%, and a starch yield ranges from 11.2-12.0 tons/ha.

*Cassava varieties KM568, KM537, KM539, KM569, KM94\** are subject to regulations governing the DUS and VCU testing. These regulations align with the circular governing the testing and recognition of new agricultural plant varieties issued by the MARD, as stipulated in the Law on Cultivation No.31/2018/QH14, effective January 1, 2020. The purpose of these regulations is to prevent the premature propagation of cassava varieties that

have not undergone rigorous testing and lack sufficient self-declaration information. This measure aims to mitigate potential damage to the investments made by farmers, businesses, and stakeholders across the cassava production, processing, and business value chain [84].

M.T.T. Nguyen, et al. (2021, 2024) [10, 11] proposed solutions for sustainable cassava development in the period 2021-2025 in Phu Yen province recommend a selection of Vietnamese cassava varieties. These include KM568, KM539, KM537, KM569, KM94\*, HN1, KM440, KM419, KM7, STB1, KM414, KM98-7, KM140, and KM98-1. Among these, cassava varieties KM568, KM539, and KM537 exhibit high starch yield and resistance to major pests and diseases, coupled with a short growth duration. Notably, the Phu Yen yellow cassava variety, KM569, is particularly esteemed for its

taste. These four new cassava varieties hold potential to address the current production requirements of the Southeast region, the Central Highlands region, and the South-Central Coast cassava region. The existing structure of Vietnamese cassava varieties stems from a robust cassava genetic foundation, representing a primary solution for sustaining and advancing cassava cultivation.

#### 4. Promising cassava varieties for the cassava program in Vietnam

H. Ceballos, et al. (2021) [92] reviewed the results of global cassava breeding over the past 50 years. Vietnam’s cassava breeding program consulted CIAT’s cassava breeding achievements and lessons from advanced countries to choose the appropriate method for the VNCP.

**Table 1. Progress of Vietnamese cassava varieties 1975-present with 16 popular cassava varieties and 4 promising cassava varieties KM568, KM537, KM539, KM569.**

Varieties/ author/year of certification	Parents/genetic genealogy	Growth duration (month)	Fresh root yield (tons/ha)	Root starch content (%)	Root starch yield (tons/ha)	Harvest index HI (%)
KM568 <sup>(10)</sup>	KM440 x (KM419 x KM539)	8-10	54.0	28.4	15.3	65
KM537 <sup>(10)</sup>	(KM419 x KM539) x KM440	8-11	51.3	28.3	14.6	64
KM539 <sup>(10)</sup>	C39* select C39 from CIAT	8-10	45.9	27.9	12.8	61
KM569 <sup>(10)</sup>	(SM2949-1 x HL23) x KM539	7-9	36.0	26.3	9.5	63
HN1 <sup>(7a, 7b)</sup>	TMEB419	8-10	42.5	27.5	11.7	61
KM419 <sup>(5, 6, 9, 10)</sup>	BKA900 x KM98-5	8-10	49.6	28.9	13.9	64
KM440 <sup>(5, 6, 9, 10)</sup>	KM94 mutation	8-10	48.7	28.7	12.3	61
KM397 <sup>(5, 6, 9, 10)</sup>	SM937-26 x BKA900	8-10	45.6	28.4	11.8	63
KM444 <sup>(5, 6, 9, 10)</sup>	XVP x GM444-2	9-11	43.8	27.9	10.4	63
KM414 <sup>(5, 6, 9, 10)</sup>	KM325 x La Tre	8-10	41.4	27.8	11.3	62
KM7 <sup>(8, 10)</sup>	SM937-26 x BKA900	8-10	40.0	27.9	10.3	65
HLS12 <sup>(4)</sup>	HL-S10 x KM140	8-10	38.4	26.6	9.6	62
KM101 <sup>(4)</sup>	CMR 29-56-101	8-10	45.0	27.7	12.5	64
KM140 <sup>(2)</sup>	(R5xR1) x KM36	8-10	39.6	28.1	10.3	67
KM98-7 <sup>(3)</sup>	SM1717 x CM321-188	9-11	31.9	27.3	9.3	65
KM98-5 <sup>(2)</sup>	R90 x KM98-1	8-10	34.5	28.5	9.8	63
KM98-1 <sup>(2)</sup>	R1xR5 seed from CIAT	8-10	32.2	27.6	8.9	66
SM937-26 <sup>(2)</sup>	seeds SM937 from CIAT	8-10	32.6	28.3	9.5	64
KM94 <sup>(2)</sup>	KM50 from Thailand	9-11	33.0	28.7	9.5	54
HL23 <sup>(1)</sup>	Local variety	8-10	29.8	25.3	7.5	53

Source: (1): [20]; (2): [85]; (3): [27]; (4): [71, 83]; (5): [1]; (6): [5]; (7): [78, 79]; (8): [73, 74]; (9): [86-89]; (10): [10, 11, 70, 90, 91].



**Table 2. Fresh root yield (tons/ha) of ten cassava varieties in eight cassava variety trials in Phu Yen province in 2022-2023.**

Varieties	Trials of 27 cassava varieties		DUS experiments with ten cassava varieties		VCU experiments with ten cassava varieties				Average fresh tuber yield (tons/ha)
	Spring	Summer	Spring	Summer	Dong Xuan		Song Hinh		
					Spring	Summer	Spring	Summer	
KM568	54.7	52.7	55.4 <sup>a</sup>	50.7 <sup>a</sup>	55.7 <sup>a</sup>	51.2 <sup>a</sup>	58.3 <sup>a</sup>	53.3 <sup>a</sup>	54.0
KM569	38.5	35.8	37.5 <sup>d</sup>	33.6 <sup>cd</sup>	36.8 <sup>d</sup>	33.6 <sup>c</sup>	39.1 <sup>de</sup>	33.1 <sup>g</sup>	36.0
KM539	48.6	43.5	47.2 <sup>abc</sup>	41.5 <sup>b</sup>	47.5 <sup>bc</sup>	42.6 <sup>b</sup>	49.6 <sup>c</sup>	46.7 <sup>cd</sup>	45.9
KM440	53.7	51.9	52.6 <sup>a</sup>	45.9 <sup>ab</sup>	54.3 <sup>ab</sup>	47.5 <sup>ab</sup>	56.3 <sup>ab</sup>	51.4 <sup>ab</sup>	51.7
KM419	52.9	47.7	49.5 <sup>ab</sup>	48.7 <sup>a</sup>	48.8 <sup>ab</sup>	46.4 <sup>ab</sup>	50.6 <sup>c</sup>	48.2 <sup>bc</sup>	49.1
KM537	55.6	47.6	53.4 <sup>a</sup>	48.7 <sup>a</sup>	55.5 <sup>a</sup>	49.1 <sup>a</sup>	52.4 <sup>bc</sup>	48.1 <sup>bc</sup>	51.3
KM536	52.4	45.5	51.6 <sup>a</sup>	47.6 <sup>a</sup>	51.5 <sup>ab</sup>	45.8 <sup>ab</sup>	51.8 <sup>bc</sup>	43.4 <sup>de</sup>	48.7
KM535	38.9	38.7	39.8 <sup>cd</sup>	35.9 <sup>c</sup>	38.6 <sup>d</sup>	35.7 <sup>c</sup>	42.3 <sup>d</sup>	38.9 <sup>ef</sup>	38.6
KM534	44.7	36.5	42.5 <sup>bcd</sup>	35.4 <sup>c</sup>	41.3 <sup>cd</sup>	36.9 <sup>c</sup>	40.4 <sup>d</sup>	39.1 <sup>ef</sup>	39.6
KM94*	35.8	31.2	37.6 <sup>d</sup>	30.5 <sup>d</sup>	37.5 <sup>d</sup>	32.5 <sup>c</sup>	35.4 <sup>e</sup>	34.7 <sup>fg</sup>	34.4
CV (%)			6.88	4.48	6.23	5.56	4.26	4.23	
F test			13.6**	47.1**	20.5**	25.8**	44.1**	42.7**	

In the same column, numbers with the same letters indicate statistically insignificant differences; ns: the difference is not meaningful; \*\*: meaningful difference  $\alpha=0.01$ ; TB = Average. Source: [11].

Some promising cassava varieties have been identified and introduced in Tables 2 and 3 after DUS and VCU trials in Vietnam [11].

The goals of the cassava genetic improvement program in Vietnam for the period 2021-2025, with a vision to 2030, are as follows:

1. To increase yield potential, dry matter content, starch content, and resistance to a number of major diseases (mainly CMD and CWBD).

2. To choose a cassava variety with an ideal cassava plant shape: straight plant, 2.5-2.9 m height, few branches, many tubers, uniform, suitable for increased planting density, and capable of early harvesting.

3. To identify high-yielding, key pest-resistant varieties suitable for different agro-ecological zones and promote their integration into smallholder farming systems.

4. To select the best key commercial cassava varieties to serve starch production, processing, and exportation. Therefore, the selection, breeding, and testing of DUS and VCU [93] helped determine selection and breeding strategies to increase cassava productivity, agricultural

digital transformation, and to build the Vietnamese cassava brand.

5. There are many new cassava varieties that have been bred and selected to be suitable for human food, dining, and ecotourism purposes, delicious, rich in carotene, yield >25 tons/ha, not bitter, low HCN content <5 mg/100 g fresh tubers.

Thanks to the financial support of the Phu Yen Province, research and breeding of cassava varieties with high starch yield, resistance to major pests and diseases, and suitability to the production conditions of Phu Yen province and other ecological regions met an urgent demand from farmers. The objectives were to select and create cassava varieties with high starch yield (at least 10% higher than controls KM419 and KM94), resistant to major pests and diseases, with a grade 1-2 disease score for CMD, and cassava witches' broom disease (CWBD), under production conditions in Phu Yen province. The research method was carried out according to VNCP & CIAT standards "Technological process of hybrid cassava selection and breeding". The results identified three promising cassava varieties KM568, KM539, and KM537 (Table 3).

**Table 3. Characteristics of cassava varieties KM568, KM539, KM537, and KM440, KM419, KM94 as checks.**

QCVN and UPOV criteria for evaluating cassava varieties	KM568 <sup>6</sup>	KM539 <sup>5</sup>	KM537	KM440 <sup>3</sup>	KM419 <sup>2</sup>	KM94* <sup>1,4</sup>
Growing duration (month)	8-10	8-11	8-11	8-10	8-10	9-11
Fresh tuber yield (tons/ha)	54.0	45.9	51.3	51.7	49.1	34.4
Yield potential (tons/ha)	70.0	50.0	50.0	60.0	60.0	40.0
Dry matter ratio (%)	40.0	39.1	39.9	39.6	40.3	40.5
Starch content (%)	28.4	27.9	28.5	28.3	28.8	28.6
Starch yield (tons/ha)	15.1	12.4	14.6	14.0	14.1	9.8
Productivity of dried chips (tons/ha)	21.6	17.9	20.5	20.4	19.8	13.9
Main pest resistance						
+ Leaf mosaic virus CMD	1.5	1.0	1.5	2.0	3.0	3.0
+ Cassava witches' broom disease (CWBD)	1.0	1.0	1.0	1.0	1.0	3.0
+ Leaf blight disease (CBB)	2.0	2.0	2.0	2.0	2.5	2.5
+ Root rot disease	2.0	2.5	2.0	2.5	2.5	2.5
+ Pink mealy bug	3.0	3.0	3.0	3.0	3.0	3.0
+ Red spider	3.0	3.5	3.5	3.0	3.0	3.0
Characteristics DUS similar to cassava						
+ Plant evaluation score	10	9	9	10	10	8
+ Root evaluation score	10	9	9	10	10	9
+ Harvest index (%)	63	61	64	64	61	57
+ Plant height (m)	2.3-2.7	2.7-3.0	2.5-2.9	2.3-2.7	2.3-2.7	2.8-3.5
+ Straight and curved plant shape	Straight	Straight	Straight	Straight	Straight	Curved
+ Degree of branching	Little	Little	Little	Little	Little	Little
+ Stem colour	Green grey	Green brown	Green brown	Green grey	Green grey	Green brown
+ Leaf colour	Green purple	Green purple	Green purple	Green purple	Green purple	Purple
+ Leaf stem colour	Green red	Green red	Green red	Green	Green red	Green
+ Number of tubers per stem (tubers/root)	8-14	7-12	7-12	8-14	8-14	6-11
+ Outer skin colour	White grey	Brown grey	Brown grey	White grey	White grey	Brown grey
+ Flesh colour	Cream	Cream	Cream	Cream	Cream	Cream
+ Cassava root form	Cylinder	Cylinder	Cylinder	Cylinder	Cylinder	Cylinder

*KM568*, a hybrid of *KM440* x (*KM419* x *KM539*), yielded fresh tubers at 54 tons/ha (56% higher than *KM94* and 10% higher than *KM419*); starch content reached 28.4% at harvest after planting 10 months, resistant to CMD at a level of 1.5 and resistant to CWBD at a level of 1, with less tuber rot, red spider mite, and pink mealy bug; a harvest index of 0.63, uniform tuber size, 8-14 tubers/root, white flesh; with the ideal new plant type shape: straight and compact, erect stems, short internodes, less

branching, plant height of 2.3-2.7 m, suitable for high planting density of 14,285 cuttings/ha.

*KM539* cassava variety was selected from the original C39 cassava variety imported from CIAT in 2004, which was selected and improved through many cycles, using technologies of double haploid hybrid cassava lines from CIAT & VNCP standards. The fresh tubers yield of *KM539* was 45.9 tons/ha (33% higher than *KM94* but

7% lower than KM419); starch content reached 27.9% at harvest after planting 10 months, resistant to CMD at a level of 1.0; resistant to CWBD at a level of 1, with less tuber rot, red spider mite, but medium pink mealy bug; a harvest index of 0.61, uniform tuber size, 7-12 tubers/root, white root flesh; with an ideal new plant type shape: straight, compact, and erect stems, short internodes, less branching, plant height of 2.7-3.0 m, suitable for high planting density of 14,285 cuttings/ha.

According to the DUS technical description of UPOV plant variety protection: variety name, variety author, year of publication: (1) Cassava variety KM94 [21, 85]; (2) Cassava variety KM419 [58]; (3) Cassava variety KM419 and cassava variety KM440 [70]; (4) The cassava variety K94\* had been upgraded by sexually crossing KM94 x KM539 to add the CMD and CWBD resistance genes of KM539 into the widely adapted cassava variety KM94; (5) KM539 cassava variety was developed from the original C39 cassava variety imported from CIAT in 2004, and had been trained and upgraded through many cycles, using techniques and technology to create double haploid hybrid cassava lines (doubled haploid). CIAT & VNCP standards [56, 59]; (6) Cassava variety KM568, the cross of KM440 x (KM419x KM539) criteria evaluated and compared with V.A. Nguyen, et al. (2021) [76].

*KM537*, a hybrid of (KM419 x KM539) x KM440, yielded fresh tubers at 51.3 tons/ha (49% higher than KM94 and 4.5% higher than KM419); starch content reached 28.5% at harvest after planting 10 months, resistant to CMD at a level of 1.5; resistant to CWBD at a level of 1, with less tuber rot, red spider mite; a harvest index of 0.64, uniform tuber size, 7-12 tubers/root, white flesh; ideal new plant type shape: straight and compact, erect stems, short internodes, less branching, plant height of 2.5-2.9m, suitable for high planting density of 14,285 cuttings/ha.

*KM569*, the Phu Yen yellow cassava variety, is a cassava variety that is prioritised for preserving delicious fresh cassava gene sources. *KM569* cassava variety was selected through 8 cycles with two trials groups of 27 cassava varieties, two DUS trials of 10 cassava varieties, and 4 basic trials of 10 cassava varieties in spring and summer crops on red and grey soils in Phu Yen province (Tables 2 and 3).

## 5. Conservation and sustainable development of Vietnamese cassava

The project titled “Conservation and sustainable development of cassava in Vietnam” yielded significant success, evidenced by trial and demonstration results in Tay Ninh, Dak Lak, Phu Yen, and Dong Nai provinces. Farmers adopting improved technologies and practices saw cassava yields surge from 8.5 tons/ha to 36 tons/ha, marking a more than fourfold increase. This outcome encapsulates the culmination of Vietnamese cassava breeding progress from 1975 to 2016, prioritising the preservation and development of suitable and sustainable cassava varieties [1]. Recent advancements in selecting Vietnamese cassava varieties and implementing ten techniques for intensive cassava farming were showcased through key demonstrations in Tay Ninh, Dak Lak, and Phu Yen provinces, predominantly employing cassava variety KM419. This variety boasted a fresh tuber yield of approximately 42-55 tons/ha (28% higher than KM94), starch content ranging from 28-31%, early maturity, and an ideal tuber and plant shape, suitable for increased planting density [5]. The combined usage of cassava varieties KM419 and KM440, alongside ten cassava intensification techniques, produced remarkable transformational outcomes in trials across the three provinces [86, 94, 95]. Notably, KM419 and KM440 comprised nearly 85% of the cassava area in Phu Yen province in 2019.

The high-yielding KM440 cassava variety, resistant to CMD disease at level 2, underwent traditional crossbreeding with the elite clone of (KM419 x KM539) - a high-yield, CMD-resistant variety at level 1. Subsequently, line selection was conducted using the pedigree method to identify cassava varieties with high starch yield, pest and disease resistance, short growth duration, and optimal plant shape. This approach presents a feasible and effective solution for sustainable cassava development [10]. KM440 and KM419 currently account for 54% of the cassava area in Tay Ninh and over 60% in Dak Lak province while awaiting the conversion of more disease-resistant cassava varieties.

The project “Research on developing cassava varieties with high starch yield, resistance to major pests and diseases, suitable for production conditions in Phu Yen province” has expanded its research scope to address

the needs of impoverished communities in challenging areas, characterised by indigenous minority groups and unique farming practices. The adoption of promising cassava varieties KM568, KM539, KM537, and KM569, coupled with the establishment of an efficient 10T cassava cultivation model, emerges as a key solution to preserve and develop sustainable cassava programs in Phu Yen province. In addition to the promising cassava varieties such as KM568, KM539, and KM537, which offer high starch yield and resistance to CMD leaf mosaic disease, Vietnam's cassava program today must focus on preserving and disseminating the Phu Yen yellow cassava variety KM569. The hybridisation of cassava varieties at CIAT, seed hybridisation, and selection in Vietnam are illustrated in Fig. 1, Tables 1-3 [11].

The Phu Yen yellow cassava variety KM569, a hybrid of SM2949-1 x HL23 x KM539, is the outcome of sexual hybridisation between the yellow cassava variety developed by H. Ceballos (2018) [28] (SM2949-1 x HL23) and cassava variety KM539 under the Phu Yen cassava project [11]. The hybrid cross SM2949-1 x HL23 involved backcrossing the SM2949-1 cassava variety, renowned for its delightful fresh taste, with the Vietnamese cassava variety HL23. The selected cassava variety HL23, with the CIAT conservation variety code of HMC1, yielded 29.8 tons/ha with a starch content of 25.3% [15]. KM569 cassava exhibits excellent boiling quality, with orange-yellow flesh, a fresh tuber yield of 36 tons/ha, and a starch content of 26.3%. It is resistant to CMD virus leaf mosaic disease at level 1.5, resistant to CWBD cassava witches broom disease at level 1, and shows resistance against major pests and diseases affecting cassava. This variety boasts an ideal cassava plant shape, with a harvest index of 61-63%, uniformly large tubers, 6-11 tubers per root, a smooth tuber shape, straight plant canopy, a plant height of 2.7-2.9 m, with 1.5-2.3 plants per bush, minimal branching, and suitability for high planting density of 14,500 cuttings/ha.

The provincial science and technology project "Research on developing cassava varieties with high starch yield, resistance to major pests and diseases, suitable for production conditions in Phu Yen province" has garnered attention from agricultural industries, households engaged in cassava cultivation, and has opened up numerous prospects for the Phu Yen cassava program [96, 97].

Based on the aforementioned results, five critical issues require special attention in current cassava production in Vietnam:

1. Cassava varieties with high starch yield, resistant to main pests CMD, CWBD, suitable for local production conditions.
2. Ten techniques for intensive cassava farming (10T).
3. Building gardens to develop lines from the most elite hybrid cassava combinations.
4. Applying technology to improve the agricultural value chain, especially cassava varieties and raw material areas, and communication to connect markets.
5. Developing appropriate and sustainable cassava production and consumption systems.

The ten techniques for intensive cassava farming (10T) encompass:

1. Utilising the best cassava cuttings of the most suitable cassava variety.
2. Identifying the optimal planting and harvest times to achieve maximum starch yield and economic efficiency.
3. Applying NPK fertiliser combined with microbial organic fertiliser and manure to enhance soil fertility and increase productivity.
4. Determining the optimal planting density for the best cassava varieties and suitable soil types.
5. Implementing IPM integrated control measures for pest-resistant cassava varieties.
6. Intercropping cassava with peanuts and legumes, planting cover crops with beans, and rotating crops suitable for the locality.
7. Implementing weed control measures, including timely weeding, herbicide application, mulching, and appropriate crop rotation.
8. Employing suitable land preparation techniques for cassava cultivation to protect soil fertility against erosion.
9. Developing a water management system for cassava cultivation.
10. Providing training on effective and appropriate cassava production, processing, and consumption value chains.

The cassava industry currently faces an imbalance between raw materials and processing products. Existing cassava raw material areas fail to meet factory requirements. Cassava and cassava product exports have exceeded 1 billion USD, with China being the primary consumer market [98]. While Vietnam's cassava selection and breeding technology connects OCOP with the new rural program, the production, processing, and consumption chain remains inadequate, resulting in a limited range of deeply processed products. Preserving and developing suitable and sustainable cassava varieties present both a new challenge and an opportunity.

## 6. Conclusions

Vietnamese cassava progression (1975 - present) has evolved through six stages, with five waves of restructuring cassava varieties to meet target orientation, farming conditions, and market requirements, resulting in the identification of 16 popular cassava varieties and 4 promising cassava varieties.

The current structure of Vietnam's cassava varieties necessitates the preservation and conservation of popular varieties suited to Vietnam's ecological regions, such as KM440, KM419, KM94, KM7, STB1, KM414, KM98-7, KM140, KM98-5, and KM98-1, while also promoting promising varieties like KM568, KM539, KM537, KM569, and HN1.

Selecting cassava varieties with high starch yield and disease resistance, and establishing a suitable and effective cassava cultivation model of 10T for Vietnamese cassava varieties such as KM568, KM539, KM537, KM569, and KM94 (also known as KU50 or KM94, preserved and developed sustainably through multiple breeding and selection cycles in Vietnam), represents a pivotal solution for conserving and sustaining the development of appropriate cassava programmes.

Despite significant achievements in breeding, selecting, developing, testing, demonstrating, and disseminating new cassava varieties, the cassava variety supply chain still faces numerous shortcomings and new challenges. The current mixture of good and bad cassava varieties leads to production and investment losses.

This literature review, titled "Progress in developing Vietnamese cassava varieties from 1975 to the present," aims to summarise nearly 50 years of progress in

enhancing Vietnamese cassava varieties. This compilation of information on Vietnamese cassava genetic resources is vital for the conservation and sustainable development of cassava programmes in Vietnam.

## CRedit author statement

Long Hoang: Conceptualisation, Methodology, Software, Writing - Original draft preparation; Mai T.T. Nguyen: Data curation, Co-Writing - Original draft preparation; Doan N.Q. Nguyen: Visualisation, Investigation; Kim Hoang: Supervision, Reviewing and Editing; Clair Hershey: Software, Validation; Reinhardt Howeler: Methodology, Reviewing and Editing.

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## COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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