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BIO 402

PRINCIPLES OF PLANT AND ANIMAL BREEDING

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Course code: BIO 402

Course title: Principles of Plant and Animal Breeding

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Series 1: Foundations of Plant and Animal Breeding

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Introduction

Plant and animal breeding is the science of improving the genetic composition of plants and animals to enhance their value to human society. Through deliberate selection, crossing, and evaluation over successive generations, breeders develop varieties and breeds with higher yield, better quality, disease resistance, adaptation to local environments, and other desirable traits. The principles underlying these practices draw on genetics, statistics, physiology, and agronomy, making breeding one of the most applied and consequential biological sciences.

Nigeria's agricultural economy depends critically on both crop and livestock production; breeding improvements have historically delivered some of the largest productivity gains in Nigerian agriculture, from the high-yielding maize and cassava varieties developed by IITA to the trypanotolerant N'Dama cattle maintained in the forest zone. This Series introduces the definition, history, objectives, and genetic foundations of plant and animal breeding, surveys the importance of breeding for Nigerian food security and livestock productivity, and introduces the principles of selection, heritability, and genetic gain that underpin all breeding programmes.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 1.1** define plant and animal breeding, describe their historical development, and state the objectives of breeding programmes (Linked to Part 1.1),
- **SLO 1.2** explain the genetic basis of breeding including the roles of variation, heredity, and selection (Linked to Part 1.1),
- **SLO 1.3** describe the importance of plant breeding for crop improvement and food security in Nigeria and name the principal plant breeding institutions (Linked to Part 1.2),
- **SLO 1.4** describe the importance of animal breeding for livestock improvement in Nigeria and name the principal animal breeding institutions (Linked to Part 1.3),
- **SLO 1.5** distinguish between natural and artificial selection and explain how each operates in breeding practice (Linked to Part 1.4), and

- **SLO 1.6** define heritability, explain the breeder's equation, and calculate expected genetic gain from selection (Linked to Part 1.4).

1.1 Introduction to Plant and Animal Breeding

1.1.1 Definition, scope, and history of plant and animal breeding

Plant breeding is the science and art of changing the genetic constitution of plants to produce varieties better suited to human needs. It encompasses all methods of creating, selecting, and evaluating genetic variation in crop plants, from traditional farmer selection to modern molecular breeding and genetic modification. Animal breeding is the analogous science applied to domesticated animals; it uses knowledge of genetics and statistics to design mating systems that improve the frequency of desirable alleles in a population over successive generations. Both disciplines share the same genetic principles but differ in the biology of their subjects: plants may be self-pollinated or cross-pollinated, diploid or polyploid; animals are predominantly cross-fertilising diploids with longer generation intervals.

Domestication of crop plants began approximately 10,000 to 12,000 years ago in multiple centres of origin including the Fertile Crescent (wheat, barley), East Asia (rice, soybean), Mesoamerica (maize, bean, squash), and sub-Saharan Africa (sorghum, pearl millet, yam, cowpea). Early farmers selected plants with non-shattering seed heads, larger seeds, and more palatable fruits over centuries of unconscious selection. Scientific plant breeding began in the late nineteenth century with the rediscovery of Mendel's laws (1900) and was transformed by the development of hybrid maize in the 1920s to 1930s (Shull, East, Jones) and the Green Revolution high-yielding wheat and rice varieties of the 1960s (Borlaug, Chandler). Animal domestication began similarly; scientific animal breeding developed with the quantitative genetic theories of Fisher (1918) and Lush (1940s).

Fill in the blank: The rediscovery of Mendel's laws of inheritance in _____ provided the scientific foundation for systematic plant and animal breeding, explaining how discrete heritable factors (genes) segregate and recombine across generations.

1.1.2 Objectives and importance of breeding programmes

The primary objectives of a breeding programme depend on the crop or species and the target environment, but commonly include: increasing yield per unit area or per animal; improving product quality (nutritional composition, processing quality, palatability); enhancing resistance or tolerance to biotic stresses (pests and diseases) and abiotic stresses (drought, heat, waterlogging, soil acidity); adapting varieties or breeds to specific agro-ecological zones; shortening the growth cycle or generation interval; improving harvest index or feed conversion efficiency; and maintaining or improving genetic diversity as insurance against new stresses.

The importance of achieving these objectives is greatest in developing countries where food insecurity is acute and where smallholder farmers depend on crop and livestock performance for their livelihoods. In Nigeria, the development of early-maturing drought-tolerant maize varieties by IITA has allowed rain-fed maize cultivation in drier Guinea savanna areas previously considered unsuitable; trypanotolerant cattle breeds (N'Dama, West African Shorthorn) allow livestock production in tsetse-infested forest and forest-savanna mosaic zones where exotic zebu breeds cannot survive. Without breeding improvement, the productivity gains required to feed Nigeria's rapidly growing population (estimated to exceed 400 million by 2050) would be impossible to achieve.

Fill in the blank: A breeding programme designed to improve _____ tolerance in maize allows cultivation in drier areas of the Guinea savanna where unpredictable rainfall would otherwise cause crop failure, directly improving food security for smallholder farmers.

1.1.3 Genetic basis of breeding: variation, heredity, and selection

All breeding depends on genetic variation: differences in allele frequencies among individuals in a population. Without variation, selection cannot change the genetic composition of a population across generations. Genetic variation arises from mutation (the ultimate source of new alleles), recombination during meiosis (which creates new combinations of alleles on chromosomes), and gene flow between populations. In breeding practice, variation is introduced or maintained by: crossing genetically diverse parents; using wild relatives or landraces as sources of novel alleles;

inducing mutation with physical or chemical mutagens; and, in modern breeding, transferring genes through transformation or genome editing.

Heredity is the transmission of genetic information from parent to offspring. Mendelian heredity governs discrete (qualitative) traits controlled by one or a few genes with large individual effects; quantitative heredity governs continuous (metric) traits such as yield, body weight, and milk production that are controlled by many genes each of small effect (polygenes) and strongly influenced by environment. Breeding for quantitative traits requires statistical methods (quantitative genetics) to separate genetic from environmental effects and to predict the response to selection. Selection is the differential survival and reproduction of genotypes; artificial selection by the breeder replaces or supplements natural selection to increase the frequency of alleles that improve the target traits.

Fill in the blank: Traits controlled by many genes each of small effect, such as grain yield and body weight, are called _____ traits; breeding improvement of these traits requires statistical quantitative genetics methods to separate genetic from environmental sources of variation.

Pilot questions 1.1

1. Define plant breeding and animal breeding and state three objectives common to both.
2. Describe the historical development of scientific plant breeding from the rediscovery of Mendel's laws to the Green Revolution.
3. Distinguish between qualitative and quantitative traits and explain why different genetic approaches are needed for each.
4. Explain the three sources of genetic variation that a breeder can exploit and state how each arises.
5. Why is genetic variation a prerequisite for any breeding programme? What would happen if a population had no genetic variation?

1.2 Importance of Plant Breeding

1.2.1 Crop improvement and food security in Nigeria

Nigeria is the most populous country in Africa and faces an ongoing food security challenge driven by population growth, climate variability, post-harvest losses, and historically low

agricultural productivity. Plant breeding has made, and continues to make, direct contributions to Nigerian food security by developing crop varieties that produce more food per unit of land, labour, and input. The key contributions include: higher-yielding varieties of staple crops (maize, rice, cassava, sorghum, cowpea, yam) that have raised yield ceilings above those of traditional landraces; early-maturing varieties that escape terminal drought and allow double-cropping; varieties with improved nutritional quality (provitamin A cassava; high-iron cowpea) that address micronutrient deficiencies; and varieties with resistance to endemic diseases (cassava mosaic virus, maize streak virus, late blight of potato) that reduce yield losses.

IITA (International Institute of Tropical Agriculture, Ibadan) has been central to crop improvement in Nigeria since its establishment in 1967; it has released improved varieties of cassava, maize, cowpea, soybean, yam, plantain, and banana that are now grown by millions of Nigerian farmers. The National Cereals Research Institute (NCRI, Badeggi) focuses on rice, maize, sorghum, and millet improvement; the National Root Crops Research Institute (NRCRI, Umudike) on yam, cassava, cocoyam, and sweet potato; and the Institute for Agricultural Research (IAR, Zaria) on dryland cereals and grain legumes for northern Nigeria. Cumulative productivity gains from improved varieties have been estimated to have contributed significantly to reducing per capita food insecurity in Nigeria, despite the challenges of variety adoption, seed system access, and input supply.

Fill in the blank: The International Institute of Tropical Agriculture (IITA), headquartered in _____, has been the leading institution for crop improvement in Nigeria since 1967, releasing improved varieties of cassava, maize, cowpea, soybean, and yam grown by millions of Nigerian farmers.

1.2.2 Development of improved crop varieties

An improved crop variety is one that has been systematically selected or bred to perform better than existing varieties in defined target environments for one or more traits. The development process follows a standard pipeline: (1) germplasm collection and evaluation: diverse plant materials (landraces, wild relatives, elite lines) are assembled and screened for useful variation;

(2) crossing: selected parents with complementary traits are hybridised to combine desirable alleles; (3) selection: progeny are evaluated over multiple generations in target environments and the best individuals are selected; (4) evaluation trials: advanced lines are tested in multi-location trials across target agro-ecological zones to assess yield stability; (5) variety release: promising lines that consistently outperform checks are submitted to a national variety release committee for official registration; (6) seed production and dissemination: certified seed of released varieties is multiplied and distributed to farmers through seed companies and extension services.

In Nigeria, new varieties must be registered with the National Centre for Genetic Resources and Biotechnology (NACGRAB) and approved by the National Variety Release Committee (NVRC) before they can be officially promoted. The variety release process ensures that new varieties have been adequately tested for yield, disease resistance, and adaptation across Nigeria's diverse agro-ecological zones. Key improved varieties released in Nigeria include: IITA TMS 30572 and TMS 4(2)1425 cassava (high dry-matter, mosaic-resistant); SAMMAZ (early-maturing maize varieties from IITA and NCRI); IT97K-499-35 cowpea (dual-purpose; high-yielding; Striga-tolerant); and FARO 44 rice (high-yielding; upland-adapted).

Fill in the blank: Before a new crop variety can be officially promoted to Nigerian farmers, it must be registered with NACGRAB and approved by the National Variety _____ Committee, which verifies that the variety has been adequately tested across multiple agro-ecological zones.

1.2.3 Roles of plant breeding institutions in Nigeria

Nigeria's plant breeding capacity is distributed across several federal research institutes, each mandated for specific crop groups. The International Institute of Tropical Agriculture (IITA, Ibadan) operates internationally but with a strong Nigeria mandate; it leads on cassava, maize, cowpea, soybean, yam, and banana/plantain. The National Cereals Research Institute (NCRI, Badeggi, Niger State) is mandated for rice, maize, sorghum, and millet. The National Root Crops Research Institute (NRCRI, Umudike, Abia State) covers yam, cassava, cocoyam, and sweet potato. The Institute for Agricultural Research (IAR, Zaria, Kaduna State) focuses on cotton, groundnut, cowpea, sorghum, millet, and wheat for the Sudan and Sahel zones. The Cocoa Research Institute of Nigeria (CRIN, Ibadan) covers cocoa, kola, cashew, coffee, and rubber.

Additional institutions include: the Rubber Research Institute of Nigeria (RRIN, Benin City); the National Horticultural Research Institute (NIHORT, Ibadan), mandated for vegetables, fruits, and ornamentals; the Forestry Research Institute of Nigeria (FRIN, Ibadan) for tree species; and various university departments of plant breeding and crop improvement at the University of Ibadan, Ahmadu Bello University, University of Agriculture Abeokuta (now Federal University of Agriculture Abeokuta), and others. The National Agricultural Seeds Council (NASC) regulates the seed industry, enforces seed quality standards, and manages the variety registration system. Collaboration between these institutions, international centres (CIMMYT, CIP, WARDA/Africa Rice), and private seed companies determines the pipeline of new varieties reaching Nigerian farmers.

Fill in the blank: The _____ Research Institute (NCRI), located in Badeggi, Niger State, is the federal institution mandated for the improvement of rice, maize, sorghum, and millet in Nigeria.

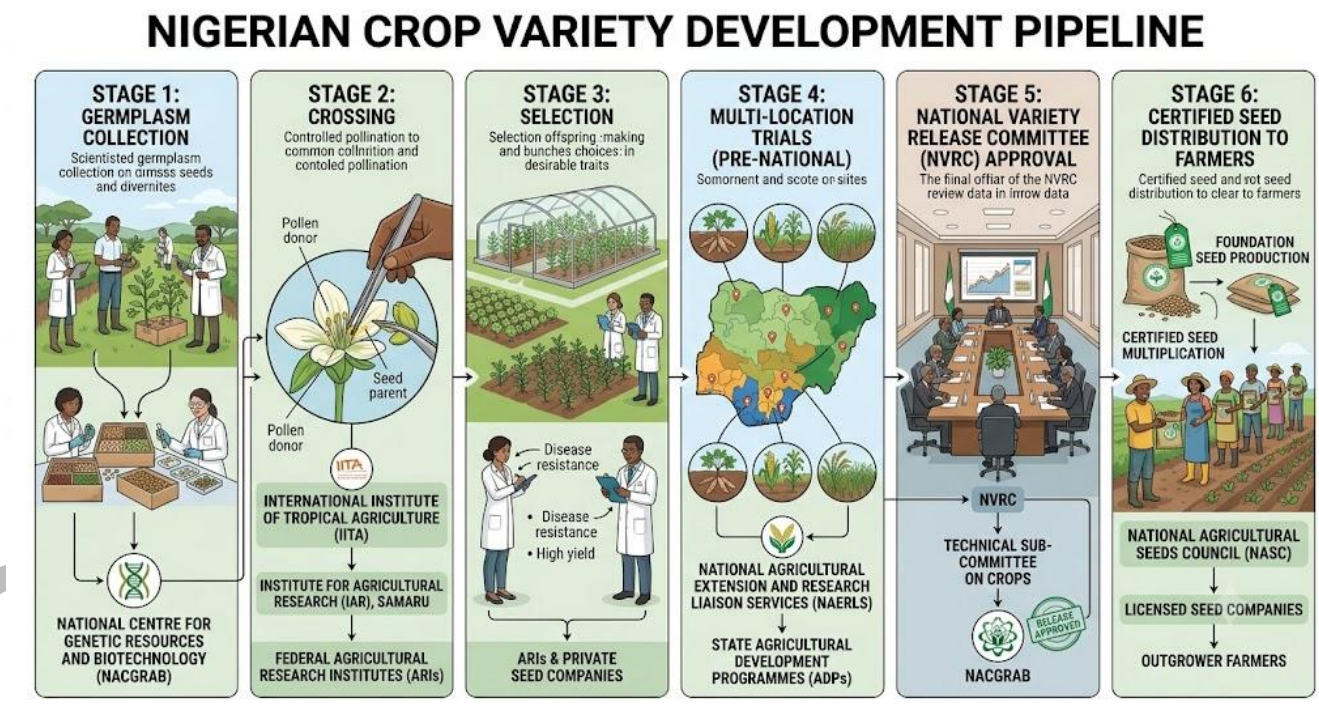


Figure 1.1: The Nigerian crop variety development pipeline from germplasm to farmer

Pilot questions 1.2

1. Explain four ways in which plant breeding has contributed to food security in Nigeria.

2. Describe the six stages of the crop variety development pipeline in Nigeria.
3. Name five Nigerian plant breeding institutions and state the crop mandate of each.
4. Explain the role of NACGRAB and the NVRC in the Nigerian variety release process.
5. Give two examples of improved crop varieties developed for Nigerian farmers and state the key traits improved in each.

1.3 Importance of Animal Breeding

1.3.1 Livestock improvement and productivity

Animal breeding improves the genetic potential of livestock populations to increase their productivity, efficiency, and adaptability. The principal livestock species in Nigeria are cattle, sheep, goats, pigs, poultry, and fish (in aquaculture). Breeding improvement aims to increase: milk yield and composition in dairy cattle; growth rate, feed conversion efficiency, and carcass quality in beef cattle, sheep, goats, and pigs; egg number and egg weight in poultry; reproductive efficiency (fertility, litter size, calving or lambing interval) across species; and disease resistance, particularly resistance to trypanosomiasis, Newcastle disease, and helminth parasites.

The economic importance of livestock breeding improvement in Nigeria is illustrated by the contrast between traditional unimproved local breeds and improved or crossbred animals. Local zebu cattle (White Fulani, Red Bororo) produce an average of 400 to 800 litres of milk per lactation; improved Holstein-Friesian crosses can produce 2,000 to 4,000 litres under intensive management in Nigeria's humid south. Local Isa Brown and Nigerian ecotype poultry produce 60 to 100 eggs per year; improved commercial layers produce 250 to 300 eggs per year. However, exotic breeds often perform poorly under Nigerian conditions due to heat stress, disease challenge, and limited nutrition; crossbreeding between exotic and local breeds to combine high productivity with local adaptation is therefore the dominant strategy in Nigerian animal improvement.

Fill in the blank: Crossbreeding between high-producing exotic breeds (e.g. Holstein-Friesian) and locally adapted breeds (e.g. White Fulani) aims to combine the high _____ potential of the exotic parent with the heat tolerance and disease resistance of the local parent.

1.3.2 Development of improved livestock breeds in Nigeria

Improved livestock production in Nigeria relies on three strategies: selection within local breeds to increase the frequency of superior genotypes; crossbreeding between local and exotic breeds to exploit heterosis and combine desirable traits; and the introduction of fully exotic breeds under intensive management. Selection within local breeds has been most successful for trypanotolerant cattle (N'Dama in south-west and central Nigeria; West African Dwarf in the forest zone) and for local poultry ecotypes adapted to scavenging production systems. Crossbreeding programmes have produced Frisian x White Fulani dairy crosses at the National Animal Production Research Institute (NAPRI) and at several state government farms; Landrace x Large White pigs at the National Veterinary Research Institute (NVRI, Vom, Plateau State); and Broiler x local chicken crosses for improved meat production.

Artificial insemination (AI) has been used to distribute superior sire genetics without physical transportation of bulls; government AI centres at NAPRI (Shika, Kaduna State) and state veterinary departments hold frozen semen from proved sires. Embryo transfer (ET) allows a genetically superior female (dam) to produce far more offspring than naturally possible by stimulating superovulation, collecting multiple embryos, and transferring them to surrogate recipient dams. Both AI and ET remain expensive and technically demanding for most Nigerian smallholder producers, limiting their uptake outside government and university farms. Recent work by IITA and the International Livestock Research Institute (ILRI) has focused on genetic characterisation of Nigerian livestock breeds and the development of genomic selection tools appropriate for resource-poor environments.

Fill in the blank: Artificial insemination (AI) allows the genetics of a superior _____ to be distributed to a large number of females without physical transportation, using frozen semen stored and distributed from government AI centres such as NAPRI in Shika, Kaduna State.

1.3.3 Roles of animal breeding institutions in Nigeria

The principal federal institution for animal breeding research in Nigeria is the National Animal Production Research Institute (NAPRI), located at Shika, Zaria (Kaduna State), which is a centre of ARCN (Agricultural Research Council of Nigeria). NAPRI conducts research on cattle, sheep,

goat, pig, poultry, and rabbit breeding; maintains foundation herds of White Fulani, Red Bororo, N'Dama, and Muturu cattle; and operates the national AI centre. The National Veterinary Research Institute (NVRI, Vom, Plateau State) focuses on livestock health, vaccine development, and disease-related breeding research. The Livestock Investigation Centre at Fashola (Oyo State) maintains improved breeds for south-western Nigeria.

At the university level, departments of Animal Science at Ahmadu Bello University (ABU, Zaria), University of Ibadan, Federal University of Agriculture Abeokuta (FUNAAB), University of Agriculture Makurdi (now Federal University of Agriculture, Makurdi), and Michael Okpara University of Agriculture (Umudike) conduct breeding research and train animal breeders. The International Livestock Research Institute (ILRI, headquartered in Nairobi but with West African programmes) collaborates with Nigerian institutions on small ruminant and cattle genetic improvement. State Agricultural Development Programmes (ADPs) operate multiplication farms that distribute improved breeds and crossbred animals to farmers. The National Agricultural Seeds Council (NASC) equivalent for livestock is the Animal Identification and Traceability System (AITS) administered by NAFDAC and the Federal Ministry of Agriculture.

Fill in the blank: The National Animal Production Research Institute (NAPRI), located at Shika, Zaria, operates under _____ (Agricultural Research Council of Nigeria) and is the principal federal institution for livestock breeding research; it maintains foundation herds of Nigerian cattle breeds and operates the national AI centre.

Pilot questions 1.3

1. State four objectives of animal breeding programmes in Nigeria and explain why crossbreeding is the dominant strategy for cattle improvement.
2. Describe the three strategies used for improving livestock in Nigeria and give one example of each.
3. Explain how artificial insemination improves the rate of genetic gain in livestock breeding.
4. Name four Nigerian animal breeding institutions and state the mandate or livestock species focus of each.

5. Compare the milk production of an unimproved White Fulani cow with a Holstein-Friesian cross and explain the genetic basis for the difference.

1.4 Principles of Selection and Improvement

1.4.1 Types of selection: natural and artificial

Selection is the process by which certain genotypes contribute more offspring to the next generation than others, causing a change in allele frequencies over time. Natural selection operates when differential survival and reproduction result from the interaction of an organism's phenotype with its natural environment, without human intervention; it tends to maintain fitness-related traits (disease resistance, drought tolerance, reproductive efficiency) but does not necessarily improve traits valued by humans. Artificial selection is the deliberate choice by a breeder or farmer of individuals with superior performance in desired traits as parents of the next generation; it replaces or supplements natural selection to accelerate improvement of economically important traits.

Three modes of artificial selection are used in breeding: (1) mass selection: individuals are selected on the basis of their own phenotype (individual performance); simple and low-cost; most effective for highly heritable traits. (2) Progeny testing: individuals are selected based on the performance of their offspring; most appropriate for traits expressed in only one sex (milk yield in cows: bulls are selected by the performance of their daughters) or traits with low heritability. (3) Family selection: individuals are selected based on the average performance of their family (full or half-sibs); useful when individual records are unreliable or when heritability is low. Modern genomic selection (using dense SNP marker panels to predict breeding values directly from genotype data) is increasingly applied to livestock and some crops, bypassing the need for progeny testing.

Fill in the blank: In animal breeding, selecting a bull for dairy improvement based on the milk yield records of his daughters rather than on his own performance is called _____ testing; it is used because bulls do not produce milk and cannot be evaluated directly for this trait.

1.4.2 Heritability and selection response

Heritability (h2) is the proportion of phenotypic variation in a population that is attributable to additive genetic differences among individuals. It ranges from 0 (all phenotypic variation is environmental; selection is ineffective) to 1 (all phenotypic variation is genetic; selection is perfectly effective). High heritability (h2 above 0.5) means that offspring tend to resemble their selected parents closely; low heritability (h2 below 0.2) means that much of the phenotypic variation is environmental and selection response is slow. Examples of heritability estimates for Nigerian livestock: milk yield in cattle h2 approximately 0.25 to 0.35; body weight in cattle h2 approximately 0.35 to 0.45; litter size in pigs h2 approximately 0.10 to 0.15; egg number in poultry h2 approximately 0.15 to 0.25.

Narrow-sense heritability (h2 = VA/VP, where VA is additive genetic variance and VP is total phenotypic variance) is the relevant measure for predicting response to selection, because only additive genetic effects are reliably transmitted from parent to offspring. Broad-sense heritability (H2 = VG/VP, where VG is total genetic variance including dominance and epistasis) is used in plant breeding contexts where clonal reproduction or inbreeding can fix non-additive effects. Realised heritability is estimated empirically as the ratio of the observed response to selection to the selection differential; it is the most practically useful estimate because it is measured in the actual breeding population under local conditions.

Fill in the blank: Narrow-sense heritability (h2) is defined as the ratio of _____ genetic variance (VA) to total phenotypic variance (VP); it is the appropriate measure for predicting response to mass selection because only additive effects are consistently transmitted from selected parents to their offspring.

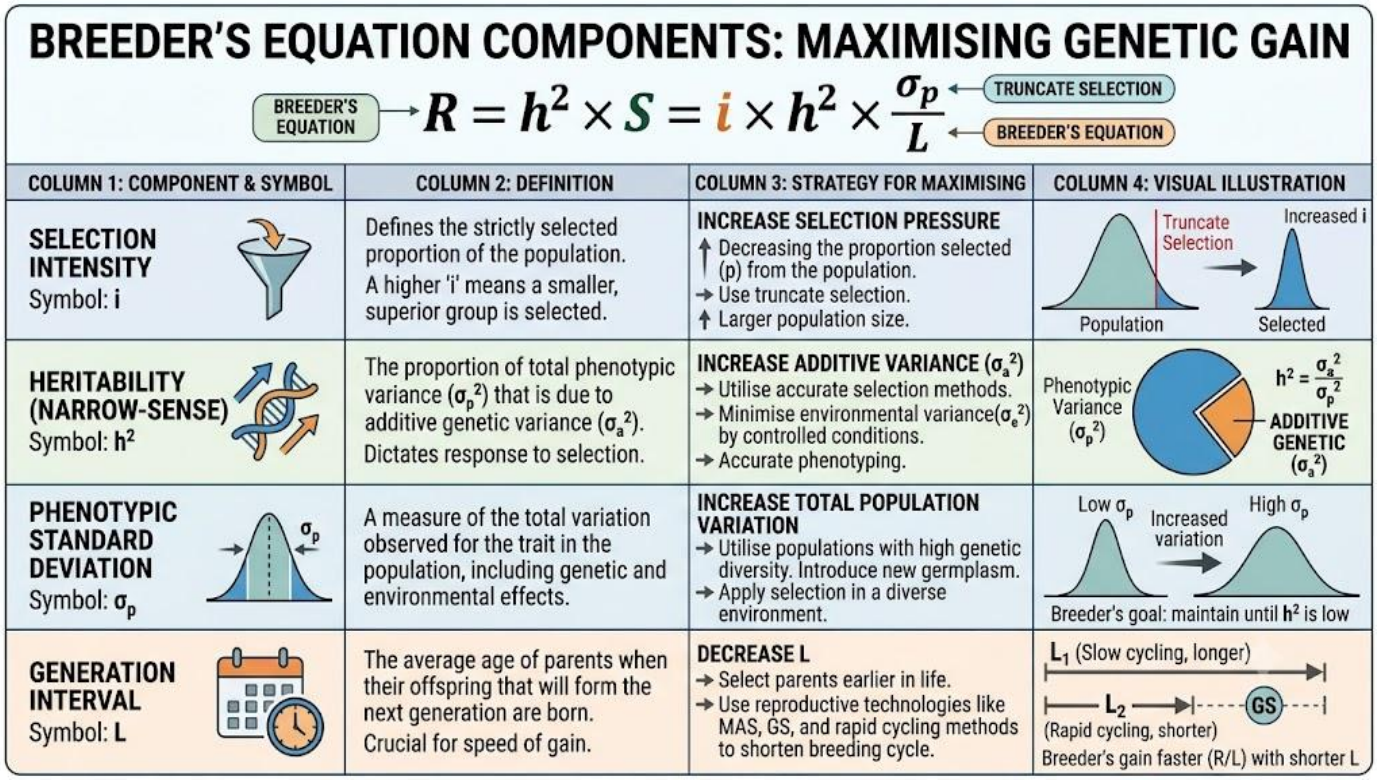
1.4.3 Genetic gain and the breeder’s equation

The breeder’s equation expresses the expected genetic gain (ΔG) from one cycle of selection: ΔG = (i x h2 x σP) / L, where i is the selection intensity (standardised selection differential; determined by the proportion of individuals selected as parents), h2 is the narrow-sense heritability of the trait, σP is the phenotypic standard deviation of the trait, and L is the generation interval (the average age of parents when their offspring are born). Genetic gain is

therefore increased by: selecting more intensively (selecting a smaller proportion of candidates); working with traits of higher heritability; increasing phenotypic variation; and shortening the generation interval.

In practice, these four components often trade off: selecting more intensively may require evaluating a larger population, increasing cost; shortening the generation interval in animals (e.g. selecting at 1 year rather than 3 years of age) may require using selection criteria assessed before full expression of the trait; and very high selection intensity reduces the effective population size, increasing inbreeding. Nigerian breeding programmes face additional constraints of limited resources, small population sizes, and the need to balance genetic gain in target traits with maintenance of genetic diversity for long-term resilience. Understanding the breeder's equation allows breeders to identify which component offers the greatest practical scope for increasing genetic gain in their specific context.

Fill in the blank: According to the breeder's equation, genetic gain (ΔG) can be increased by shortening the _____ interval (L), which is the average age of parents at the birth of their offspring; this is why genomic selection, which allows selection at a younger age, accelerates genetic gain in livestock breeding.



Box 1.1: Components of the breeder's equation and strategies for increasing genetic gain

Pilot questions 1.4

1. Distinguish between mass selection, progeny testing, and family selection, and state when each is most appropriate.
2. Define heritability and explain why narrow-sense heritability (h2) is more useful than broad-sense heritability (H2) for predicting response to selection.
3. State the breeder's equation and explain what each component represents.
4. A maize breeder selects the top 10 percent of plants from a population with mean yield 3.0 t/ha and standard deviation 0.6 t/ha. The heritability of yield is 0.35 and generation interval is 1 year. Calculate the expected genetic gain per year.
5. Explain why intensive selection (selecting a very small proportion of candidates) may not always be the best strategy in a small Nigerian breeding population.

Series Summary

Plant breeding involves changing the genetic composition of plants to develop improved varieties, while animal breeding applies the same principles to domesticated animals. Both fields developed scientifically after the rediscovery of Mendel's laws in 1900 and were later advanced through quantitative genetics, hybrid technology, and molecular and genomic tools. Their major objectives include increasing yield, improving quality, strengthening resistance to diseases and environmental stress, and enhancing local adaptation. Genetic variation, heredity, and selection are the three foundations of breeding: variation provides the raw material for improvement, heredity ensures that useful traits are passed to offspring, and selection increases the frequency of desirable alleles and phenotypes.

In Nigeria, plant breeding has improved food security through varieties such as IITA TMS cassava, SAMMAZ maize, IT97K cowpea, and FARO 44 rice, developed by institutions including IITA, NCRI, NRCRI, IAR, and CRIN. New varieties usually pass through germplasm collection, crossing, selection, multi-location testing, NVRC release, and NASC-regulated seed production. Animal breeding commonly uses selection within local breeds, crossbreeding, artificial insemination, and embryo transfer, with research led by institutions such as NAPRI, NVRI, and university animal science departments. Major selection methods include mass selection, progeny testing, and family selection. Heritability is expressed as $\mathbf{h^2 = VA / VP}$, while expected genetic gain is calculated using the breeder's equation: $\mathbf{\Delta G = (i \times h^2 \times \sigma P) / L}$.

Glossary of Terms

- **Additive genetic variance (VA):** the component of genetic variance attributable to the average effects of alleles summed across loci; the only component of genetic variance that is reliably transmitted from parent to offspring and that determines response to mass selection.
- **Artificial insemination (AI):** the manual introduction of collected and processed semen into the reproductive tract of a female animal; used in livestock breeding to distribute superior sire genetics widely and to accelerate genetic gain.
- **Artificial selection:** the deliberate choice by a breeder of individuals with superior phenotypic performance as parents of the next generation; replaces or supplements natural selection to improve economically important traits.
- **Breeder's equation:** the formula $\Delta G = (i \times h2 \times \sigma P) / L$ expressing expected genetic gain per generation as a function of selection intensity, heritability, phenotypic standard deviation, and generation interval.
- **Crossbreeding:** the mating of individuals from genetically different breeds or varieties to combine desirable traits and exploit heterosis; the dominant livestock improvement strategy in Nigeria.
- **Generation interval (L):** the average age of parents at the birth of their offspring; one of the four components of the breeder's equation; shortening L increases the rate of genetic gain per unit time.
- **Genetic gain (ΔG):** the expected change in the population mean of a trait per generation of selection, as predicted by the breeder's equation; the primary measure of breeding programme effectiveness.
- **Germplasm:** the total genetic diversity contained in a collection of plant or animal material (seeds, accessions, breeds, wild relatives) that serves as the raw material for breeding programmes.
- **Heritability (h2):** the proportion of phenotypic variation in a population attributable to additive genetic differences; narrow-sense heritability (VA/VP) predicts response to mass selection; ranges from 0 to 1.
- **Mass selection:** a form of artificial selection in which individuals are chosen as parents based solely on their own phenotypic performance; simplest and least expensive selection method; most effective for highly heritable traits.

- **Polygenic trait:** a quantitative trait controlled by many genes each of small effect; examples include grain yield, body weight, and milk production; requires quantitative genetic approaches for breeding improvement.
- **Progeny testing:** a method of evaluating an individual's breeding value by measuring the performance of its offspring; used for traits expressed in only one sex or for traits with low heritability.
- **Quantitative genetics:** the branch of genetics that uses statistical methods to analyse continuously varying traits influenced by many genes and the environment; provides the theoretical foundation for all plant and animal breeding.
- **Selection intensity (i):** the standardised selection differential; a measure of how rigorously individuals are screened before being chosen as parents; determined by the proportion of the population selected; higher i increases genetic gain.
- **Variety release:** the formal process by which a new crop variety is officially registered and approved for promotion to farmers after testing by the National Variety Release Committee (NVRC) and registration with NACGRAB.

Concept Check Questions [Series 1]

Objective Questions

1. The formula $\Delta G = (i \times h2 \times \sigma P) / L$ is called the _____'s equation; it quantifies expected genetic gain per generation from selection. (Linked to SLO 1.6)
2. The proportion of phenotypic variation attributable to additive genetic differences among individuals is called _____ heritability, symbolised h2. (Linked to SLO 1.6)
3. The principal Nigerian federal institution for crop improvement of rice, maize, sorghum, and millet is the National _____ Research Institute (NCRI) at Badeggi. (Linked to SLO 1.3)
4. Selecting a bull for dairy merit based on the milk yield of his daughters rather than his own performance is called _____ testing. (Linked to SLO 1.5)
5. The science of changing the genetic constitution of plants to produce varieties better suited to human needs is defined as plant _____. (Linked to SLO 1.1)

Short-Answer Questions

6. State four objectives common to plant and animal breeding programmes and explain why each is important in the Nigerian context. (Linked to SLO 1.1)
7. Explain the three sources of genetic variation available to a breeder and give one example of how each is exploited in Nigerian crop improvement. (Linked to SLO 1.2)
8. Name four Nigerian plant breeding institutions and state the crop mandate of each. (Linked to SLO 1.3)
9. Distinguish between mass selection, progeny testing, and family selection and state one situation in Nigerian agriculture where each is most appropriate. (Linked to SLO 1.5)
10. Define the four components of the breeder's equation and explain how a Nigerian cattle breeder could increase genetic gain for milk yield. (Linked to SLO 1.6)

Long-Answer Questions

11. Explain the history and genetic basis of plant and animal breeding. Describe how genetic variation, heredity, and selection interact to produce improvement over successive generations. Use specific examples from Nigerian agriculture. (Linked to SLOs 1.1, 1.2)
12. Discuss the importance of plant breeding for food security in Nigeria. Describe the crop variety development pipeline, name the principal institutions involved, and give two examples of improved varieties released for Nigerian farmers. (Linked to SLOs 1.3)
13. Explain the importance of animal breeding in Nigeria. Describe the three improvement strategies and the roles of the principal institutions. Define heritability, state the breeder's equation, and calculate expected genetic gain for a trait with h2 = 0.30, selection intensity i = 1.76 (top 10 percent), phenotypic standard deviation 50 kg, and generation interval 3 years. (Linked to SLOs 1.4, 1.5, 1.6)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. Breeder.
2. Narrow-sense.
3. Cereals.
4. Progeny.
5. Breeding.

Short-Answer Questions

6. (1) Increased yield: essential to feed Nigeria's growing population without expanding arable land area. (2) Disease resistance: reduces crop losses to endemic diseases (cassava mosaic virus, maize streak virus) and livestock losses to trypanosomiasis and Newcastle disease. (3) Stress adaptation (drought, heat): allows production in marginal environments and in the face of climate variability, securing smallholder livelihoods. (4) Improved quality (nutrition, processing): addresses micronutrient deficiency (provitamin A cassava, high-iron cowpea) and enhances value for food processing industries.
7. Mutation (ultimate source of new alleles; exploited in Nigerian crop improvement by using mutagenesis to develop new sorghum and groundnut variants at IAR Zaria). Recombination during meiosis (creates new allele combinations; exploited by crossing diverse parents in cassava, maize, and cowpea breeding programmes at IITA). Gene flow between populations (introduction of exotic varieties or wild relatives as parents; exploited by using CIMMYT maize germplasm in NCRI and IITA maize breeding to introduce new alleles for drought tolerance and streak resistance).
8. IITA (Ibadan): cassava, maize, cowpea, soybean, yam, banana/plantain. NCRI (Badeggi): rice, maize, sorghum, millet. NRCRI (Umudike): yam, cassava, cocoyam, sweet potato. IAR (Zaria): cotton, groundnut, cowpea, sorghum, millet, wheat for dryland zones. CRIN (Ibadan): cocoa, kola, cashew, coffee, rubber.
9. Mass selection: individuals chosen based on their own phenotype; most appropriate for highly heritable traits such as seed size, days to maturity, and body conformation in Nigerian smallholder cattle selection. Progeny testing: individuals evaluated by offspring performance; appropriate for milk yield in Nigerian dairy bulls (bulls cannot be assessed directly for milk yield; their genetic merit is estimated from daughters' records at NAPRI Shika). Family selection: individuals chosen based on sibling performance; appropriate when individual records are unreliable or for traits with low heritability such as litter size in Nigerian village pigs where environmental conditions are highly variable.
10. i (selection intensity): the standardised selection differential; determined by the proportion of candidates selected; increase by evaluating a larger candidate pool and selecting fewer as parents. h2 (narrow-sense heritability): proportion of phenotypic variation that is additive genetic; cannot be directly controlled but can be estimated more accurately with larger datasets. σP (phenotypic standard deviation): spread of trait values; increase by using genetically diverse foundation stock from Nigerian and international germplasm banks. L (generation interval): average parental age at

offspring birth; a cattle breeder can increase genetic gain by using AI with semen from genotypically selected young bulls (reducing L from 5 to 6 years to 2 to 3 years) and by implementing genomic selection to allow bull selection at 6 months rather than after progeny testing at 3 to 4 years.

Long-Answer Questions

11. History: plant domestication began approximately 10,000 to 12,000 years ago (sorghum and pearl millet in West Africa; wheat in Fertile Crescent; rice in East Asia; maize in Mesoamerica). Early farmer selection: unconscious selection for non-shattering heads, larger seeds, palatable fruits over thousands of years. Scientific plant breeding: Mendel's laws rediscovered 1900; hybrid maize developed 1920s to 1930s (Shull, East, Jones); Green Revolution high-yielding wheat and rice 1960s (Borlaug). Animal breeding: domestication co-occurred with plants; scientific foundation: Fisher's quantitative genetics (1918); Lush's animal breeding theory (1940s). Genetic basis: variation (mutation; recombination; gene flow) provides raw material; without variation, selection cannot change population. Heredity: Mendelian (qualitative traits: one or few genes; large effects; segregate discretely) vs quantitative (polygenic traits: many genes; small individual effects; continuous distribution; yield, body weight, milk). Selection: natural (fitness-related; maintains adaptation); artificial (replaces natural; accelerates change in desired direction). Interaction: maize example in Nigeria: IITA breeders cross diverse parents (combining Suwan1 tropical adapted line with CIMMYT drought-tolerant germplasm); progeny segregate due to recombination; breeders select the highest-yielding individuals in dry conditions (artificial selection for drought tolerance and yield); selected lines transmit additive alleles to offspring (heredity); after several cycles, population mean yield under drought stress increases measurably (genetic gain).
12. Importance of plant breeding for food security: (1) higher-yielding varieties raise yield ceiling above landraces (IITA cassava TMS varieties yield 25 to 40 t/ha fresh root vs 10 to 15 t/ha for landraces); (2) early-maturing varieties (SAMMAZ early maize) allow double-cropping and escape terminal drought; (3) disease-resistant varieties (mosaic-resistant cassava; streak-resistant maize) reduce post-planting losses; (4) nutritionally improved varieties (provitamin A cassava; high-iron cowpea) address micronutrient deficiency in rural households. Pipeline: (1) Germplasm collection and evaluation at NACGRAB gene bank and IITA/NCRI genebanks; screen for useful variation. (2) Crossing: selected parents with complementary traits hybridised at IITA, NCRI, NRCRI, IAR. (3) Selection: progeny evaluated in replicated trials over 4 to 6 seasons; best lines advanced. (4) Multi-location evaluation trials: advanced lines tested across agro-ecological zones

in Nigeria (forest, savanna, Sahel). (5) Variety release: NVRC reviews data; approves lines that outperform checks for yield, disease resistance, and quality. (6) Seed production: NASC-certified seed producers multiply and distribute to farmers via ADPs and private seed companies. Examples: IITA TMS 30572 cassava (high dry matter; mosaic-resistant; dual-purpose; widely grown in southern Nigeria); IT97K-499-35 cowpea (dual-purpose; high-yielding; Striga-tolerant; early-maturing; adopted across Guinea savanna).

13. Importance of animal breeding: raises productivity (milk, meat, eggs, reproductive rate); improves efficiency (feed conversion); enhances disease resistance; increases farmer income. Three strategies: (1) Selection within local breeds: maintaining N'Dama cattle in tsetse-infested south-west Nigeria for trypanotolerance; selecting high-producing White Fulani cows at NAPRI. (2) Crossbreeding: Holstein-Friesian x White Fulani for improved milk yield with heat tolerance; Landrace x Large White pigs at NVRI for improved litter size and growth rate. (3) AI and ET: NAPRI AI centre distributes frozen semen from proved White Fulani and Friesian x Fulani bulls to improve national herd; ET allows high-producing cows to produce more calves. Institutions: NAPRI (Shika, Zaria; cattle, sheep, goat, pig, poultry, rabbit breeding; national AI centre); NVRI (Vom, Plateau State; livestock health, pig breeding, vaccine development); ABU (Zaria; university research on beef cattle and small ruminants); FUNAAB (Abeokuta; pig, poultry, and small ruminant research). Heritability: h2 = VA/VP; proportion of phenotypic variation due to additive genetic differences; h2 = 0 means selection is ineffective (all variation environmental); h2 = 1 means phenotype perfectly predicts breeding value. Breeder's equation: $\Delta G = (i \times h2 \times \sigma P) / L$. Calculation: i = 1.76 (top 10 percent); h2 = 0.30; σP = 50 kg; L = 3 years. $\Delta G = (1.76 \times 0.30 \times 50) / 3 = 26.4 / 3 = 8.8$ kg per year. Interpretation: selecting the top 10 percent of bulls based on estimated breeding value, with h2 of 0.30, a population standard deviation of 50 kg body weight, and a 3-year generation interval, is expected to increase population mean body weight by 8.8 kg per year of selection.

Answers to Pilot Questions [Series 1]

Part 1.1

1. Plant breeding: the science and art of changing the genetic constitution of plants to produce varieties better suited to human needs through deliberate selection, crossing, and evaluation. Animal breeding: the use of genetic and statistical principles to design mating systems that

improve the frequency of desirable alleles in domesticated animal populations over successive generations. Three common objectives: (1) increase yield or productivity; (2) improve resistance to biotic stresses (diseases, pests, parasites); (3) enhance adaptation to local agro-ecological conditions (drought, heat, soil type).

2. Rediscovery of Mendel's laws (1900): explained discrete inheritance; allowed prediction of segregation ratios in crosses; provided theoretical basis for selecting parental lines. Development of hybrid maize (1920s to 1930s): Shull, East, and Jones demonstrated that crossing inbred lines produced heterosis (hybrid vigour); hybrid maize varieties dramatically outyielded open-pollinated varieties; commercial hybrid seed industry established. Green Revolution (1960s): Borlaug developed semi-dwarf, high-yielding, photoperiod-insensitive wheat varieties at CIMMYT; IRRI developed equivalent rice varieties; both required fertiliser input but delivered unprecedented yield gains in developing countries; reduced famine risk across Asia and parts of Africa. Post-Green Revolution molecular era: RFLP, SSR, SNP markers allowed marker-assisted selection (MAS) and genomic selection; genetic transformation and CRISPR genome editing allowed direct modification of specific genes.
3. Qualitative (Mendelian) traits: controlled by one or a few genes with large, discrete effects; phenotype falls into distinct classes (red vs white flower; resistant vs susceptible); inheritance follows Mendel's ratios (3:1, 1:1, 9:3:3:1); identified and improved by single-gene selection or backcrossing. Quantitative (polygenic) traits: controlled by many genes each of small effect; phenotype shows continuous distribution; heavily influenced by environment; examples include grain yield, body weight, milk production; identified and improved using quantitative genetic methods (heritability estimation; selection index; breeding value prediction; genomic selection). Different approaches needed because: qualitative traits can be traced through individual crosses and fixed by inbreeding; quantitative traits require statistical analysis of large populations and cannot be selected gene by gene.
4. Mutation: spontaneous changes in DNA sequence; the ultimate source of new alleles in any population; naturally rare but can be induced in crops using gamma radiation, X-rays, or chemical mutagens (EMS). Recombination during meiosis: crossing-over between homologous chromosomes creates new combinations of alleles on chromosomes; every sexual cross generates recombinant progeny; fundamental to all hybridisation-based breeding. Gene flow: movement of alleles between populations through pollen, seed, or animal migration; in plant breeding, exploited by importing germplasm from international genebanks or using wild relatives as parents; introduces alleles not present in the current breeding population.

5. Without genetic variation, all individuals in a population are genetically identical for the target trait; selection favours no individual over another; allele frequencies cannot change; the population mean cannot improve regardless of selection intensity. Breeding progress is impossible. In practice, a population with no genetic variation (fully inbred line) cannot respond to selection; the breeder must introduce new variation by crossing with genetically diverse material before selection can resume. This is why maintaining diverse germplasm collections is essential for long-term breeding progress.

Part 1.2

1. (1) Higher-yielding varieties: improved cassava (IITA TMS series, yielding 25 to 40 t/ha vs 10 to 15 t/ha for landraces) and maize (SAMMAZ; 5 to 7 t/ha vs 1 to 2 t/ha for local varieties) have raised total production without expanding farmland, directly increasing food availability per capita. (2) Disease-resistant varieties: mosaic-resistant cassava and streak-resistant maize reduce crop losses that previously caused severe food shortages in affected farming communities; disease resistance reduces dependence on expensive fungicides and insecticides. (3) Nutritionally improved varieties: provitamin A cassava and orange-fleshed sweet potato address vitamin A deficiency; high-iron and high-zinc cowpea and beans address iron and zinc deficiency in rural diets without requiring dietary diversification. (4) Early maturity and stress tolerance: early-maturing cowpea and maize allow farmers in the Guinea and Sudan savanna zones to produce a crop before terminal drought; drought-tolerant maize varieties reduce yield losses in drought years, stabilising farmer income and food supply.
2. (1) Germplasm collection and evaluation: diverse materials (landraces, wild relatives, elite lines from Nigerian and international genebanks such as NACGRAB and IITA) assembled and screened for useful variation in target traits. (2) Crossing and hybridisation: selected parents with complementary traits crossed to create F1 hybrids that combine desirable alleles; in self-pollinated crops, F1 is allowed to self for several generations to fix lines. (3) Selection: segregating progeny evaluated in replicated trials over 4 to 6 seasons; best performing lines selected based on yield, disease resistance, maturity, and quality traits. (4) Multi-location evaluation trials: advanced lines tested across multiple sites representing the target agro-ecological zones (humid forest, Guinea savanna, Sudan savanna); yield stability and wide adaptation assessed. (5) Variety release: data submitted to NVRC; independent committee reviews and approves lines that consistently outperform existing check varieties; variety registered with NACGRAB. (6) Certified seed production and distribution: approved seed producers (private companies, ADPs) multiply breeder seed through certified seed production;

distributed to farmers through input dealers, extension services, and government seed distribution programmes.

3. IITA (Ibadan): cassava, maize, cowpea, soybean, yam, banana/plantain; the largest crop improvement institution in Nigeria. NCRI (Badeggi, Niger State): rice, maize, sorghum, millet; primary mandate for cereals in Nigeria. NRCRI (Umudike, Abia State): yam, cassava, cocoyam, sweet potato; primary mandate for root and tuber crops. IAR (Zaria, Kaduna State): cotton, groundnut, cowpea, sorghum, millet, wheat; focus on dryland northern Nigeria crops. CRIN (Ibadan, Oyo State): cocoa, kola, cashew, coffee, rubber; tree crop improvement for export commodities.
4. NACGRAB (National Centre for Genetic Resources and Biotechnology, Ibadan): the national gene bank; collects, characterises, conserves, and documents plant genetic resources (landraces, wild relatives, elite lines); manages the national germplasm database; coordinates access to Nigerian genetic resources in compliance with the Convention on Biological Diversity. NVRC (National Variety Release Committee): the statutory body that evaluates data submitted by breeders from multi-location trials; independently assesses whether a candidate variety consistently outperforms existing check varieties for yield, disease resistance, and quality; approves varieties for official registration; ensures that only adequately tested varieties are recommended to farmers, protecting farmers from poorly adapted or misrepresented varieties.
5. IITA TMS 30572 cassava: improved traits include high dry-matter content (35 to 40 percent vs 25 to 30 percent for landraces; important for gari and fufu processing yield); resistance to cassava mosaic disease (CMD; caused by cassava mosaic begomoviruses transmitted by whitefly; causes 20 to 80 percent yield loss in susceptible varieties); high fresh root yield (25 to 40 t/ha). IT97K-499-35 cowpea (IITA): improved traits include dual purpose (both grain and foliage used as human food and livestock fodder); early maturity (60 to 65 days to maturity vs 80 to 90 days for local varieties; allows escape from terminal drought and double-cropping); resistance to Striga gesnerioides (witchweed; a parasitic plant causing 30 to 60 percent yield loss in cowpea in northern Nigeria); high grain yield (1.5 to 2.0 t/ha vs 0.3 to 0.5 t/ha for local varieties).

Part 1.3

1. Four objectives: (1) increase milk yield for dairy income and family nutrition; (2) increase growth rate and feed conversion efficiency for beef production; (3) improve disease resistance (trypanosomiasis, Newcastle disease, helminthiasis) to reduce treatment costs and mortality; (4) improve reproductive efficiency (litter size, calving interval, age at first calving) to accelerate genetic gain and increase total progeny output per breeding female. Crossbreeding is dominant

because: local Nigerian breeds (White Fulani, Red Bororo cattle; West African Dwarf sheep and goats) are adapted to the heat, disease, and nutritional challenges of Nigerian conditions but have low genetic potential for milk, growth, and egg production; exotic breeds (Holstein-Friesian, Large White) have high genetic potential but poor adaptation; crossbreeding combines high productivity from the exotic parent with local adaptation from the local parent; first-cross (F1) animals also benefit from heterosis (hybrid vigour) for fitness traits such as survival and reproduction.

2. (1) Selection within local breeds: selecting the highest-producing White Fulani cows and bulls at NAPRI Shika for within-breed genetic improvement; used for trypanotolerant N'Dama cattle in the forest zone where no exotic blood is introduced. (2) Crossbreeding: crossing Holstein-Friesian bulls (via AI) with White Fulani cows to produce F1 crosses with improved milk yield and partial local adaptation; Landrace x Large White pig crossbreeding at NVRI for improved litter size, growth rate, and feed conversion. (3) Artificial insemination and embryo transfer: NAPRI AI centre collects, freezes, and distributes semen from proved White Fulani and Friesian bulls to state farms and research stations; embryo transfer from high-producing F1 Friesian x Fulani cows into lower-producing White Fulani recipients allows a superior dam to produce 5 to 10 calves per year instead of one.
3. AI separates the genetic contribution of a sire from his physical location; a single superior bull can sire thousands of offspring annually (vs 30 to 50 naturally) by distributing frozen semen to farms nationwide. This increases selection intensity (i in the breeder's equation) for the sire path by allowing only the very best bulls to be used. AI also reduces the generation interval indirectly when combined with progeny testing (bulls can be selected and their semen frozen young, before full progeny data are available, and the semen released when data confirm their breeding value). In genomic selection, young bulls with high genomic estimated breeding values (GEBVs) can be used in AI immediately, shortening L further.
4. NAPRI (Shika, Zaria; Kaduna State): principal federal livestock breeding research institute; cattle, sheep, goat, pig, poultry, rabbit research; national AI centre with frozen semen bank; foundation herds of White Fulani, Red Bororo, N'Dama, Muturu cattle; operates under ARCN. NVRI (Vom, Plateau State): livestock health and disease research; pig breeding (Landrace x Large White crossbreeding programme); vaccine development; disease surveillance. ABU Department of Animal Science (Zaria): university-level cattle, sheep, and goat breeding research; training of animal scientists and geneticists; collaboration with NAPRI. ILRI West African Programme (collaborates with NAPRI and FUNAAB): genetic characterisation of Nigerian

livestock breeds; development of genomic tools for small ruminant and cattle improvement in low-input systems.

5. Unimproved White Fulani cow: average milk yield 400 to 800 litres per lactation (zebu cattle; evolved primarily for draught, meat, and some milk in semi-arid conditions; lactation length approximately 180 to 240 days). Holstein-Friesian x White Fulani F1 cross: average milk yield 2,000 to 4,000 litres per lactation under intensive management in Nigeria's humid south (Holstein-Friesian parent has been selected for milk yield over more than 100 years of intensive dairying in temperate countries; the F1 cross inherits the Holstein high-milk alleles while retaining White Fulani heat tolerance and tick resistance). Genetic basis: the difference is primarily additive genetic; Holstein-Friesian cattle carry many more favourable alleles at loci affecting mammary gland capacity, milk-let-down, prolactin response, and energy partitioning toward milk production; the F1 cross receives one set of these favourable alleles from the Holstein sire, increasing the frequency of high-milk alleles in its genome compared with a pure White Fulani.

Part 1.4

1. Mass selection: selects individuals based on their own phenotypic performance; does not require family records; most appropriate when heritability is high (h2 above 0.4), the trait is expressed in both sexes, and population size is large enough to maintain genetic diversity. Progeny testing: selects individuals based on the average performance of their offspring; most appropriate when the trait is expressed in only one sex (milk yield; egg production; litter size) or when heritability is low and individual records are unreliable. Family selection: selects individuals based on sibling (full-sib or half-sib) performance; most appropriate when individual records are expensive or impossible to obtain, heritability is low, and family sizes are large enough to give reliable family means.
2. Heritability (h2) is the proportion of phenotypic variation in a population that is due to additive genetic differences. Narrow-sense h2 = VA / VP (additive genetic variance divided by total phenotypic variance). It is more useful than broad-sense H2 = VG/VP for predicting response to selection because: only additive genetic effects (VA) are reliably passed from parent to offspring; dominance variance (VD) and epistatic variance (VI) contribute to VG but are largely dispersed in sexual reproduction and cannot be consistently selected for unless clonal propagation or full-sib mating is used; using H2 to predict selection response would overestimate the actual gain in sexually reproducing populations.

3. Breeder's equation: $\Delta G = (i \times h2 \times \sigma P) / L$. i = selection intensity (standardised selection differential; determined by the proportion of candidates selected as parents; higher i means more rigorous screening). h2 = narrow-sense heritability (proportion of phenotypic variation that is additive genetic; determines how reliably phenotype predicts breeding value). σP = phenotypic standard deviation (spread of trait values in the candidate population; larger spread gives more scope for selection). L = generation interval (average age of parents when offspring are born; shorter L means more generations per unit time and therefore faster total gain).
4. Data: mean yield = 3.0 t/ha; SD (σP) = 0.6 t/ha; top 10 percent selected; i for top 10 percent = 1.755 (standard value from selection intensity table); h2 = 0.35; L = 1 year. $\Delta G = (i \times h2 \times \sigma P) / L = (1.755 \times 0.35 \times 0.6) / 1 = 0.3686 / 1 = 0.37$ t/ha per year. Interpretation: selecting the top 10 percent of maize plants each year, with heritability of 0.35 and a yield standard deviation of 0.6 t/ha, is expected to increase population mean yield by approximately 0.37 t/ha per year of selection.
5. Very high selection intensity (selecting the top 1 to 2 percent of candidates) reduces the number of individuals contributing genes to the next generation, sharply reducing the effective population size (Ne). A small Ne means: (1) increased inbreeding accumulates each generation, reducing heterozygosity and potentially causing inbreeding depression (reduced fertility, immune function, and viability); (2) genetic drift (random changes in allele frequency) increases, causing loss of favourable alleles by chance rather than by selection; (3) the genetic diversity available for future selection in new environments or against new stresses is reduced. In a small Nigerian breeding population (e.g. 50 to 100 head of a local cattle breed), selecting only 1 to 2 sires simultaneously achieves high short-term genetic gain but risks eroding the gene pool and creating long-term vulnerability to disease or environmental change.

References and Attributions [Series 1]

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Figure 1.1: The Nigerian crop variety development pipeline from germplasm to farmer. Attribution: AI generated. Suggested OER search string: “crop variety development pipeline stages germplasm selection release seed distribution diagram OER”.
- Box 1.1: Components of the breeder’s equation and strategies for increasing genetic gain. Attribution: AI generated. Suggested OER search string: “breeder’s equation genetic gain selection intensity heritability generation interval table OER”.

Course code: BIO 402

Course title: Principles of Plant and Animal Breeding

Course credit load: 2 Units

Series 2: Cytogenetic Principles and Breeding Mechanisms

- **Part 2.1: Chromosomes and the Cell Cycle in Breeding**
  - Sub Part 2.1.1: Chromosome structure, number, and ploidy
  - Sub Part 2.1.2: Mitosis, meiosis, and their significance in breeding
  - Sub Part 2.1.3: Chromosome aberrations and their breeding consequences
- **Part 2.2: Modes of Reproduction and Their Breeding Implications**
  - Sub Part 2.2.1: Self-pollination and its consequences
  - Sub Part 2.2.2: Cross-pollination and its consequences
  - Sub Part 2.2.3: Vegetative and apomictic reproduction in breeding
- **Part 2.3: Polyploidy and Genome Manipulation**
  - Sub Part 2.3.1: Types of polyploidy and their origins
  - Sub Part 2.3.2: Breeding applications of polyploidy
  - Sub Part 2.3.3: Mutation breeding and induced mutagenesis
- **Part 2.4: Molecular Tools in Plant and Animal Breeding**
  - Sub Part 2.4.1: Molecular markers and marker-assisted selection
  - Sub Part 2.4.2: Genomic selection and its applications
  - Sub Part 2.4.3: Genetic transformation and genome editing in breeding

Introduction

Cytogenetics is the study of chromosomes, their structure, behaviour, and relationship to heredity and variation. An understanding of chromosome behaviour during mitosis and meiosis is fundamental to breeding because it explains how genes are inherited, how variation is generated, how ploidy manipulation can create new crop forms, and why certain crosses succeed or fail. Breeding mechanisms encompass the modes of reproduction (self-pollination, cross-pollination, vegetative, apomictic) that determine which genetic structures are appropriate for a given crop or species, and the tools (polyploidy induction, mutation breeding, molecular markers, genomic selection, genetic transformation) available to create and exploit variation.

This Series covers the cytogenetic foundations of breeding from chromosome structure through meiosis, aberrations, and ploidy manipulation to the molecular tools that have transformed modern plant and animal improvement. Together these topics explain why different crops require different breeding approaches and how contemporary molecular breeding accelerates genetic gain beyond what is achievable with phenotypic selection alone.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 2.1** describe chromosome structure, ploidy levels, and the significance of mitosis and meiosis in breeding (Linked to Part 2.1),
- **SLO 2.2** explain the breeding consequences of chromosome aberrations and polyploidy (Linked to Parts 2.1, 2.3),
- **SLO 2.3** distinguish between self-pollination and cross-pollination and explain how each mode of reproduction shapes the appropriate breeding method (Linked to Part 2.2),
- **SLO 2.4** describe apomixis and vegetative reproduction and explain their applications in breeding (Linked to Part 2.2),

- **SLO 2.5** explain the origins and breeding applications of polyploidy and mutation breeding (Linked to Part 2.3), and
- **SLO 2.6** describe molecular markers, marker-assisted selection, genomic selection, and genetic transformation and explain their applications in Nigerian crop and livestock improvement (Linked to Part 2.4).

2.1 Chromosomes and the Cell Cycle in Breeding

2.1.1 Chromosome structure, number, and ploidy

A chromosome is a linear DNA molecule complexed with histone proteins and packaged into a compact structure visible under the light microscope during cell division. Each chromosome consists of two sister chromatids joined at the centromere during mitosis and early meiosis; the chromatids separate at anaphase to become daughter chromosomes. The number of chromosomes per cell is a species-specific constant; the haploid number (n) refers to the gametic chromosome set, and the diploid number (2n) refers to the somatic cell set. The genomic constitution is described using the basic chromosome number (x): diploids have 2x chromosomes per cell; tetraploids have 4x; hexaploids have 6x.

Examples of chromosome numbers in Nigerian crops and livestock: maize (Zea mays; 2n = 20; diploid; x = 10); cassava (Manihot esculenta; 2n = 36; allotetraploid; x = 9); groundnut (Arachis hypogaea; 2n = 40; allotetraploid; x = 10); wheat (Triticum aestivum; 2n = 42; allohexaploid; x = 7); cotton (Gossypium hirsutum; 2n = 52; allotetraploid; x = 13); cattle (Bos taurus; 2n = 60); goat (Capra hircus; 2n = 60); sheep (Ovis aries; 2n = 54); pig (Sus scrofa; 2n = 38); chicken (Gallus gallus; 2n = 78). Knowledge of ploidy is important in breeding because it determines fertility in crosses, the inheritance of traits, and the feasibility of polyploidy manipulation.

Fill in the blank: Cassava (Manihot esculenta) is an allotetraploid with 2n = 36 chromosomes and a basic chromosome number of x = _____; its polyploid nature means that gene dosage effects and tetrasomic inheritance patterns must be considered in genetic analysis.

2.1.2 Mitosis, meiosis, and their significance in breeding

Mitosis is the cell division that produces two genetically identical daughter cells from one parent cell; it occurs in somatic tissue for growth, repair, and vegetative reproduction. Meiosis is the two-stage reduction division that produces four haploid daughter cells (gametes or spores) from one diploid parent cell; it is the basis of sexual reproduction. The key events of meiosis I are: pairing of homologous chromosomes (synapsis); crossing-over between non-sister chromatids of homologous chromosomes (chiasmata formation), which generates recombinant chromosomes; and segregation of homologous chromosomes to opposite poles, reducing chromosome number by half. Meiosis II is essentially a mitotic division of the haploid products of meiosis I.

Meiosis is central to breeding because: recombination during prophase I generates new combinations of alleles, providing the variation that selection acts upon in segregating populations; independent assortment of non-homologous chromosomes generates additional variation; and the reduction in chromosome number (2n to n) followed by fertilisation (n + n = 2n) maintains the species chromosome number across generations. In polyploid crops (cassava, groundnut, cotton), meiosis is more complex because multiple sets of homologous chromosomes may pair as multivalents, leading to irregular segregation, reduced fertility, and departure from expected Mendelian ratios. Understanding meiotic behaviour is essential for predicting segregation in crosses and for designing effective selection strategies.

Fill in the blank: The exchange of segments between non-sister chromatids of homologous chromosomes during meiotic prophase I is called _____; it produces recombinant chromosomes that carry new combinations of alleles and is the primary source of genetic variation in sexually reproducing species.

2.1.3 Chromosome aberrations and their breeding consequences

Chromosome aberrations are changes in chromosome number or structure that can arise spontaneously or be induced by mutagens. Numerical aberrations include aneuploidy (loss or gain of one or a few chromosomes: monosomic, 2n-1; trisomic, 2n+1; nullisomic, 2n-2) and polyploidy (increase in the whole genome set: triploid, 3x; tetraploid, 4x). Structural aberrations include deletions (loss of a chromosome segment), duplications (repetition of a segment), inversions (reversal of a segment), and translocations (transfer of a segment between non-

homologous chromosomes). These aberrations have both negative consequences (reduced fertility; lethality; developmental abnormalities) and useful applications in breeding.

Breeding applications of chromosome aberrations include: trisomics are used in genetic mapping to assign genes to specific chromosomes (a trisomic for chromosome 3 shows altered segregation ratios for genes on chromosome 3); nullisomics and monosomics in wheat have been used to locate genes to specific chromosomes by observing which nullisomic line loses a trait; translocations can transfer genes from wild relatives to crop chromosomes (e.g. transfer of stem rust resistance from rye to wheat via a 1BL/1RS translocation); inversions suppress recombination in a chromosomal region, locking together favourable allele combinations. In animal breeding, chromosomal translocations in pigs and cattle can cause reduced fertility and are screened for in breeding programmes.

Fill in the blank: An organism with one extra chromosome (2n+1) is called a _____; trisomics are used in breeding and genetics research to assign genes to specific chromosomes by observing altered segregation ratios in crosses involving the trisomic individual.

Pilot questions 2.1

1. Define haploid, diploid, and tetraploid and give one crop example of each chromosome level.
2. Explain why meiosis is more important than mitosis for plant and animal breeders.
3. Describe two structural chromosome aberrations and state one breeding use of each.
4. State the chromosome number (2n) of maize, cassava, groundnut, and cattle.
5. Explain how crossing-over during meiosis generates genetic variation useful for plant breeding.

2.2 Modes of Reproduction and Their Breeding Implications

2.2.1 Self-pollination and its consequences

Self-pollination (autogamy) occurs when pollen fertilises the ovules of the same flower or plant. Crops that are predominantly self-pollinating include rice, wheat, barley, sorghum, cowpea, groundnut, tomato, and soybean. Repeated self-pollination increases homozygosity at all loci:

after n generations of selfing, heterozygosity is reduced to (1/2)^n of its initial value; after 6 to 7 generations of selfing, a population approaches near-complete homozygosity (less than 1 percent heterozygosity). Self-pollinated crops are therefore naturally inbred; their varieties are essentially homozygous lines that breed true and maintain uniformity across generations.

The breeding consequences of self-pollination include: uniformity and stability of varieties make seed saving and true-to-type reproduction straightforward for farmers; inbreeding depression is minimal in naturally self-pollinated crops because deleterious recessive alleles have been exposed to selection and largely purged over evolutionary time; hybridisation between two inbred lines of self-pollinating crops can be achieved simply by growing lines adjacent to each other and removing male-fertile plants (in crops where emasculation is possible) or by using male sterility systems. Breeding methods suited to self-pollinating crops include pedigree selection, bulk method, single seed descent (SSD), and backcross breeding, all of which exploit the natural tendency toward homozygosity.

Fill in the blank: After six generations of selfing, a plant population that was initially fully heterozygous reaches approximately _____ percent homozygosity; this is the genetic basis for developing true-breeding inbred lines in self-pollinating crops such as rice, wheat, and cowpea.

2.2.2 Cross-pollination and its consequences

Cross-pollination (allogamy) occurs when pollen from one plant fertilises the ovules of a different plant. Obligate cross-pollinators include maize, rye, pearl millet, sugar beet, cassava, and most forage grasses; they maintain high levels of heterozygosity in natural populations. Mechanisms that enforce cross-pollination include: dioecy (separate male and female plants; e.g. papaya, date palm); monoecy with spatial separation of male and female flowers (e.g. maize: tassel at apex; silk at ear); dichogamy (pollen shed and stigma receptivity occurring at different times); self-incompatibility (biochemical rejection of self-pollen); and male sterility. Cross-pollinated species show high natural heterozygosity and outbreeding vigour.

Breeding consequences of cross-pollination: populations are heterozygous and genetically variable; inbreeding (forced self-pollination) causes inbreeding depression due to exposure of

deleterious recessive alleles at many loci; open-pollinated varieties (OPVs) are genetically variable mixtures; hybrid varieties produced by crossing specific inbred lines exploit heterosis but require hybrid seed production each generation. Breeding methods suited to cross-pollinating crops include mass selection, recurrent selection, and hybrid breeding. In Nigerian agriculture, hybrid maize (SAMMAZ hybrids) produced by crossing IITA-derived inbred lines has substantially outperformed OPVs; similar hybrid programmes exist for sorghum and pearl millet at IAR Zaria.

Fill in the blank: Forced self-pollination of a naturally cross-pollinating species such as maize causes _____ depression due to the exposure and expression of deleterious recessive alleles that are normally masked by dominant alleles in the heterozygous condition.

2.2.3 Vegetative and apomictic reproduction in breeding

Vegetative reproduction produces new plants from non-reproductive parts (roots, stems, leaves, tubers, corms, bulbs) without sexual fertilisation. It generates clones of the parent plant; all offspring are genetically identical to the parent. This property is enormously valuable in breeding: once a superior genotype is identified through selection or hybridisation, it can be multiplied rapidly and distributed to farmers as cuttings, tubers, or planting material that maintains genetic identity across generations. Vegetatively propagated crops important in Nigeria include cassava (stem cuttings), yam (tuber sets or minisetts), potato (tuber sets), sugar cane (stem cuttings), banana and plantain (suckers or tissue-culture plantlets), and sweet potato (vine cuttings).

Apomixis is the production of seeds without fertilisation; the embryo develops from maternal tissue (apospory, diplospory, or adventitious embryony) and is therefore genetically identical to the mother plant. Apomixis occurs naturally in some grasses (Panicum maximum, guinea grass; Brachiaria species; Pennisetum squamulatum) and some fruit trees. It is highly valuable to breeders because it allows hybrid genotypes to be fixed and reproduced through seed without loss of heterozygosity across generations; if introduced into cross-pollinating crops such as maize, it would allow farmers to save hybrid seed. Transferring apomixis from its natural hosts to major crops is an active area of research. Tissue culture and somatic embryogenesis are used

to multiply superior clonal material rapidly and to eliminate systemic viruses from planting stock.

Fill in the blank: The production of seeds without fertilisation, in which the embryo develops from maternal tissue and is genetically identical to the mother plant, is called _____; it occurs naturally in some tropical grasses such as Panicum maximum and Brachiaria species.

Pilot questions 2.2

1. Distinguish between self-pollination and cross-pollination and give two crop examples of each.
2. Explain why inbreeding depression occurs in cross-pollinated crops but not in naturally self-pollinated crops.
3. State four mechanisms that enforce cross-pollination in crop plants and give one Nigerian example of each.
4. Explain the breeding value of vegetative reproduction in cassava and yam improvement in Nigeria.
5. Define apomixis and explain why its transfer to major cross-pollinating crops such as maize would be commercially significant.

2.3 Polyploidy and Genome Manipulation

2.3.1 Types of polyploidy and their origins

Polyploidy is the condition in which an organism has more than two complete sets of chromosomes per cell. It arises naturally by failure of cell division after genome duplication (autopolyploidy), or by hybridisation between species followed by chromosome doubling (allopolyploidy). Autopolyploids contain multiple copies of the same genome (AAAA in an autotetraploid); all chromosome sets are homologous and may form multivalents (quadrivalents, hexavalents) at meiosis, leading to irregular segregation and reduced fertility. Allopolyploids

contain genome sets from two or more different species (AABB in an allotetraploid); homoeologous chromosomes pair regularly as bivalents, giving normal meiosis and high fertility.

Important crop examples: wheat (Triticum aestivum; allohexaploid; AABBDD; 2n = 42; originated by hybridisation between three wild grass species); groundnut (Arachis hypogaea; allotetraploid; AABB; 2n = 40; hybrid of A. duranensis x A. ipaensis followed by chromosome doubling); cassava (Manihot esculenta; allotetraploid; 2n = 36); cotton (Gossypium hirsutum; allotetraploid; AADD; 2n = 52). Banana (Musa spp.) cultivated in Nigeria are triploids (AAA or AAB; 2n = 33); they are seedless because odd ploidy prevents normal meiosis. Sugarcane (Saccharum officinarum) is a complex polyploid (2n = 80; octoploid). Natural polyploidy has played a major role in the evolution of many of Nigeria's most important crops.

Fill in the blank: Allopolyploids such as wheat and groundnut contain genome sets from two or more different species; they show normal meiosis because homoeologous chromosomes pair as _____, unlike autopolyploids which form multivalents and show irregular segregation.

2.3.2 Breeding applications of polyploidy

Polyploidy is exploited in plant breeding in several ways. Induced polyploidy using colchicine (a spindle poison that prevents chromosome separation at mitosis, doubling the chromosome number in treated cells) allows breeders to: double the chromosome number of a sterile interspecific hybrid to restore fertility (amphidiploidy); produce new crop forms with larger organs, increased vigour, or altered chemical composition; and combine genomes from wild relatives with crop genomes to transfer useful genes across reproductive barriers. Triploid watermelon (produced by crossing tetraploid and diploid parents) is seedless and commands a premium price; triploid sugar beet has higher sugar content than diploid beet.

In Nigeria, colchicine treatment has been used to double chromosome numbers in interspecific cassava crosses (Manihot esculenta x M. glaziovii) at IITA to produce amphidiploids that can serve as bridges for transferring disease resistance from wild Manihot species. Polyploidisation of forage grasses (Andropogon gayanus) has been explored at IAR Zaria to improve biomass yield. Allotetraploid groundnut (Arachis hypogaea) is diploid at the phenotypic level for many trait segregations because it behaves as a 'segmental allotetraploid'; understanding its genome

constitution is critical for interpreting inheritance data and designing appropriate molecular breeding approaches.

Fill in the blank: Colchicine is used to induce polyploidy in plants by inhibiting spindle formation during _____, which prevents chromosome separation and results in a cell with double the normal chromosome number; it is used to restore fertility in sterile interspecific hybrids.

2.3.3 Mutation breeding and induced mutagenesis

Mutation breeding uses physical or chemical mutagens to induce heritable changes in the genome, creating new allelic variation not present in the existing gene pool. Physical mutagens include ionising radiation (X-rays, gamma rays from cobalt-60, thermal neutrons); they cause double-strand DNA breaks that are repaired with errors. Chemical mutagens include alkylating agents such as ethyl methanesulphonate (EMS), which causes point mutations by alkylating guanine residues; sodium azide; and diethyl sulphate. Mutagen treatment generates a large population of M1 plants carrying diverse random mutations; desirable mutants are identified by screening M2 and later generations.

Over 3,000 officially released mutant varieties in more than 175 crop species are registered in the FAO/IAEA Mutant Variety Database. Notable examples include semi-dwarf wheat and rice mutants that contributed to the Green Revolution; golden promise barley (gamma-ray mutant; used in Scottish whisky malting; improved malting quality); groundnut varieties with altered oil composition developed at IAR Zaria using EMS mutagenesis; and early-maturing sorghum mutants released in Nigeria. The International Atomic Energy Agency (IAEA) operates a coordinated research programme on mutation breeding and provides technical support for mutagen treatment facilities in developing countries including Nigeria. Mutation breeding is particularly valuable when no natural variation exists for a target trait in the available germplasm.

Fill in the blank: The chemical mutagen _____ (EMS) causes point mutations by alkylating guanine residues in DNA, leading to G:C to A:T transitions in the next replication cycle; it is

widely used to generate dense mutant populations in crops where natural variation for a target trait is absent.

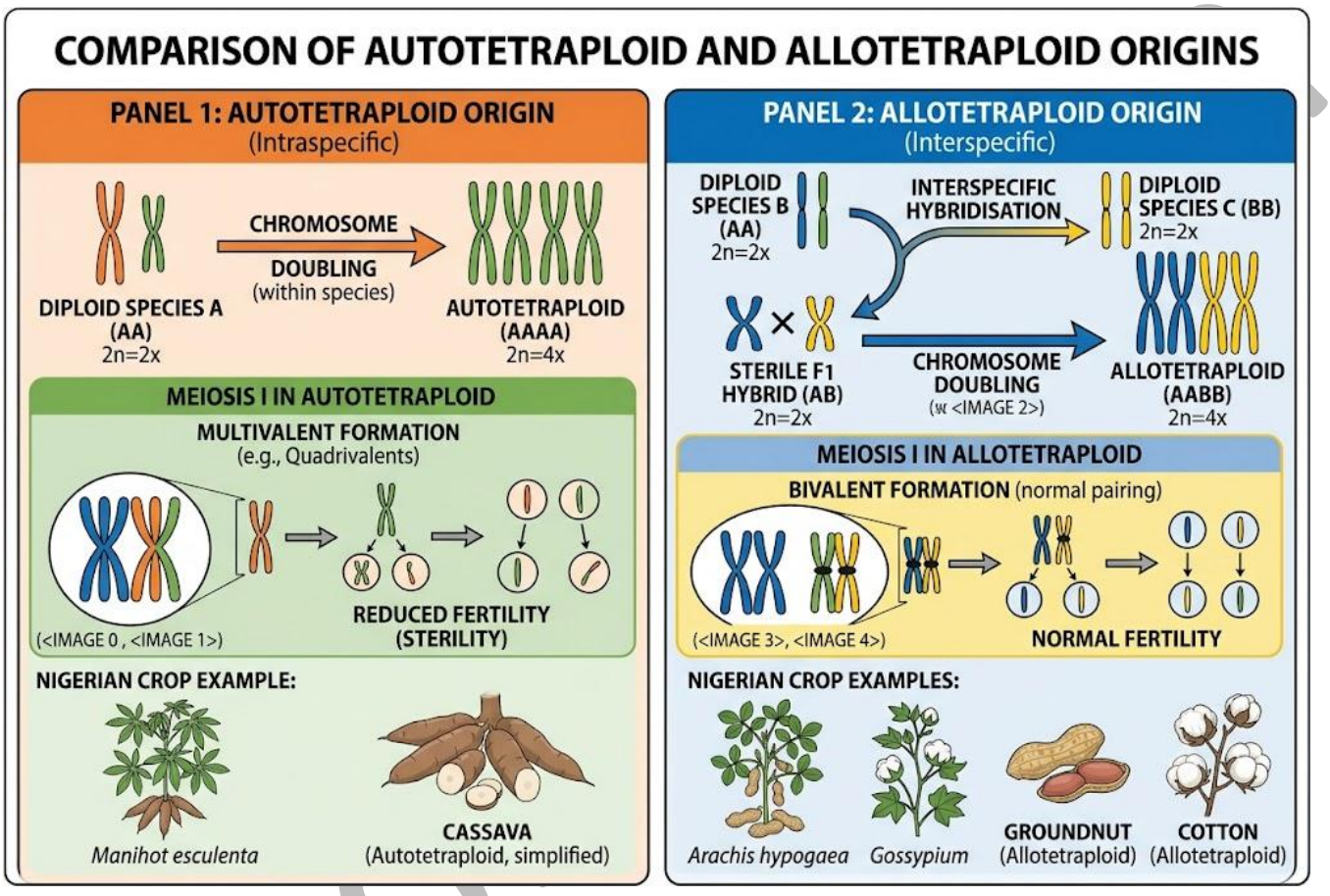

Figure 2.1: Origins and meiotic behaviour of autopolyploids versus allopolyploids

Pilot questions 2.3

1. Distinguish between autopolyploidy and allopolyploidy and give one crop example of each.
2. Explain how colchicine induces polyploidy and describe one breeding application of induced polyploidy.
3. Explain what mutation breeding is and state two types of mutagen used in crop improvement.
4. Why are triploid plants such as triploid watermelon seedless?
5. State two advantages and two disadvantages of polyploidy in crop breeding.

2.4 Molecular Tools in Plant and Animal Breeding

2.4.1 Molecular markers and marker-assisted selection

Molecular markers are DNA-sequence differences between individuals that can be detected by laboratory assays and used as indirect indicators of the presence of alleles at nearby gene loci. The principal marker types used in Nigerian crop and livestock breeding are: Restriction Fragment Length Polymorphisms (RFLPs; first generation; labour-intensive; rarely used now); Simple Sequence Repeats (SSRs or microsatellites; co-dominant; multi-allelic; highly informative; widely used for fingerprinting and diversity analysis); Single Nucleotide Polymorphisms (SNPs; most abundant; suitable for high-throughput genotyping arrays; the basis of modern genomic selection); and Sequence-Characterised Amplified Regions (SCARs) derived from RAPD markers. Dominant markers (RAPDs, AFLPs) detect presence/absence of a band but cannot distinguish heterozygotes from dominant homozygotes.

Marker-assisted selection (MAS) uses molecular markers tightly linked to a gene of interest to select for that gene indirectly, without phenotyping for the trait itself. MAS is most powerful for: qualitative disease resistance genes (R-genes) that have been mapped to a specific locus (e.g. cassava mosaic disease resistance gene CMD2 at IITA; cowpea Striga resistance QTLs); recessive alleles that cannot be identified in heterozygotes by phenotype; alleles expressed in only one environment (drought; flooding) that are expensive to phenotype; and background selection during backcross breeding to accelerate recovery of the recurrent parent genome. IITA uses MAS routinely for cassava CMD resistance and cassava brown streak disease (CBSD) resistance; the West Africa Centre for Crop Improvement (WACCI, University of Ghana) trains Nigerian plant breeders in MAS applications for cowpea, maize, and cassava.

Fill in the blank: Marker-assisted selection (MAS) uses molecular markers tightly linked to a target gene to select for that gene by _____ rather than phenotype; this is particularly useful for recessive alleles, disease resistance genes expressed only in the presence of a pathogen, and drought-tolerance alleles that require expensive managed stress screening.

2.4.2 Genomic selection and its applications

Genomic selection (GS) predicts the breeding value of an individual from its genome-wide marker genotype using a statistical model trained on a reference population of individuals with both genotype and phenotype data. Unlike MAS, which uses a small number of markers linked to known genes, GS uses thousands to hundreds of thousands of SNPs distributed across the genome to simultaneously capture the effects of all QTLs, including those with small individual effects too small to be detected by QTL mapping. The genomic estimated breeding value (GEBV) is more accurate than a traditional estimated breeding value (EBV) based on phenotype alone, especially for traits with low heritability and for individuals without phenotypic records.

GS is transforming livestock breeding in developed countries: in dairy cattle, bulls can be selected at 6 months of age based on GEBVs from a 54,000-SNP chip, rather than waiting 4 to 5 years for progeny test results; this has cut the generation interval and doubled the rate of genetic gain. Applications in Nigeria are still emerging due to cost, but the International Livestock Research Institute (ILRI) has developed low-cost 10,000-SNP chips for trypanotolerant cattle breeds and small ruminants in West Africa; IITA has implemented GS for cassava at its Ibadan headquarters, using 27,000 to 200,000 SNPs to predict yield, dry matter, and disease resistance in cassava breeding populations across Nigeria and East Africa.

Fill in the blank: Genomic selection predicts an individual's _____ estimated breeding value (GEBV) from genome-wide SNP marker data; because it captures the effects of all QTLs simultaneously, it is more accurate than traditional phenotypic selection for traits with low heritability.

2.4.3 Genetic transformation and genome editing in breeding

Genetic transformation (transgenic technology) introduces foreign DNA (a transgene) into the genome of a plant or animal using biological vectors (Agrobacterium tumefaciens for dicots; biolistics/gene gun for cereals and monocots) or direct methods (electroporation; microinjection). The transgene integrates into the host genome and is inherited in subsequent generations. Transgenic crops approved for commercial cultivation in Nigeria include Bt cowpea (expressing the Bacillus thuringiensis Cry1Ab protein for pod borer resistance; approved by NAFDAC and NBMA in 2021; developed by IITA and IAR in collaboration with the African Agricultural

Technology Foundation, AATF); Bt cotton is under regulatory evaluation. Transgenic crops must be evaluated under Nigeria's biosafety regulations governed by the National Biosafety Management Agency (NBMA) under the National Biosafety Act (2015).

Genome editing uses programmable nucleases (CRISPR-Cas9, TALENs, ZFNs) to make precise cuts in the DNA at targeted sequences, enabling deletions, insertions, or base substitutions at specific genomic loci without introducing foreign DNA. CRISPR-Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats with Cas9 nuclease) is the most widely used system; it uses a guide RNA (gRNA) complementary to the target sequence to direct the Cas9 nuclease to the correct chromosomal location. Edits that do not introduce foreign DNA may be regulated differently from transgenics; several countries distinguish SDN-1 (small deletions/substitutions at a target locus) from traditional GMOs. Applications in Nigerian crops under research include editing of the SWEET gene promoters in cassava to confer resistance to cassava bacterial blight, and editing of eIF4E gene variants in cowpea for virus resistance.

Fill in the blank: Bt cowpea expresses the _____ (Bt) protein Cry1Ab, which is toxic to the pod borer Maruca vitrata; it was approved for commercial cultivation in Nigeria in 2021, becoming one of the first biotech crops approved for smallholder farmers in sub-Saharan Africa.

Tool	Marker/Data Type	Number of Loci	Primary Application	Nigerian Example
SSR Markers	Microsatellites (short tandem repeats)	Dozens to hundreds	Genetic diversity, cultivar identification	Used in cassava and yam diversity studies at IITA Ibadan
SNP Array	Single nucleotide polymorphisms	Thousands to millions	High-resolution genotyping, genome-wide association	Applied in maize and cowpea breeding programs in Nigeria
MAS	Linked DNA markers	Few to dozens	Selection for disease	Used in rice breeding for blast

			resistance, yield traits	resistance (NCRI Badeggi)
Genomic Selection	Genome-wide SNP data	Tens of thousands	Predicting breeding values, accelerating selection	Applied in sorghum and maize improvement at IAR Zaria
Genetic Transformation	Transgenes inserted into genome	Single locus (engineered)	Introducing novel traits (e.g., pest resistance)	Trials on cowpea (*Bt cowpea*) for Maruca resistance in Nigeria
CRISPR-Cas9	Targeted genome editing	Specific loci	Precise gene knockout or modification	Emerging use in cassava virus resistance research (NACGRAB Ibadan)

Box 2.1: Comparison of molecular breeding tools and their applications in Nigerian crop and livestock improvement

Pilot questions 2.4

1. Distinguish between SSR markers and SNP markers and state one advantage of each for plant breeding.
2. Explain the difference between marker-assisted selection (MAS) and genomic selection (GS) and state one situation where each is preferred.
3. Describe how Bt cowpea was developed and state the regulatory body that approved it in Nigeria.
4. Explain how CRISPR-Cas9 genome editing works and give one potential application in Nigerian crop improvement.
5. Why does genomic selection shorten the generation interval in livestock breeding?

Series Summary

Chromosomes are DNA–protein complexes whose ploidy level, such as diploid, tetraploid, or hexaploid, influences meiosis, inheritance, and breeding strategy. Mitosis produces genetically identical cells for growth, while meiosis forms haploid gametes and creates variation through crossing-over and independent assortment. Chromosomal abnormalities, including aneuploidy, polyploidy, and structural rearrangements, may reduce fitness but can also be useful in research and breeding. Self-pollinating crops such as rice, wheat, and cowpea are naturally inbred, breed true, and are suited to pedigree and backcross breeding. Cross-pollinating crops such as maize and cassava maintain more heterozygosity, may suffer inbreeding depression, and are better suited to hybrid and recurrent selection. Vegetative propagation preserves superior genotypes in clonal crops, while apomixis maintains heterozygosity through seed production.

Polyploidy may occur through autopolyploidy, in which the same genome is doubled, or allopolyploidy, in which genomes from different species are combined, as seen in wheat, groundnut, cassava, and cotton. Colchicine can be used to induce polyploidy, while triploids are often seedless. Mutation breeding uses radiation such as gamma rays and X-rays or chemicals such as EMS to create new alleles. Molecular breeding tools include SSR and SNP markers, marker-assisted selection for linked traits such as CMD2 resistance in cassava and Striga resistance in cowpea, and genomic selection, which uses genome-wide SNPs to predict genomic estimated breeding values. Genetic transformation through Agrobacterium or biolistics and genome editing with CRISPR-Cas9 further expand available variation. Bt cowpea, approved in Nigeria in 2021, became the first biotech crop released for Nigerian smallholder farmers.

Glossary of Terms

- **Allopolyploidy:** polyploidy arising from hybridisation between two different species followed by chromosome doubling; contains genome sets from both parents; shows

normal bivalent meiosis and high fertility; examples include wheat (AABBDD), groundnut (AABB), and cassava.

- **Amphidiploidy:** an allopolyploid produced by doubling the chromosome complement of a sterile interspecific hybrid; it has the combined chromosome sets of both parental species and is normally fertile.
- **Apomixis:** the production of seeds without fertilisation; the embryo develops from maternal tissue and is genetically identical to the mother plant; occurs naturally in some grasses (Panicum maximum, Brachiaria).
- **Autopolyploidy:** polyploidy arising from doubling of a single species' genome; contains two or more identical genome sets; forms multivalents at meiosis; often shows reduced fertility compared with allopolyploids.
- **Colchicine:** an alkaloid derived from the autumn crocus (Colchicum autumnale) that inhibits spindle formation during mitosis; used to induce polyploidy by preventing chromosome separation, doubling the chromosome number.
- **CRISPR-Cas9:** a programmable genome-editing system that uses a guide RNA to direct the Cas9 nuclease to a specific DNA sequence; makes double-strand breaks enabling precise deletion, insertion, or substitution at targeted loci.
- **Crossing-over:** the exchange of chromosome segments between non-sister chromatids of homologous chromosomes during meiotic prophase I; produces recombinant chromosomes with new allele combinations; the primary source of genetic variation in sexual reproduction.
- **Genomic selection (GS):** a breeding method that uses genome-wide SNP markers to predict genomic estimated breeding values (GEBVs) for all individuals, including those without phenotypic records; allows selection at a young age, shortening the generation interval.
- **Inbreeding depression:** the reduction in fitness (growth, fertility, survival) observed when a normally cross-pollinating population is subjected to repeated self-pollination or close mating; caused by increased homozygosity for deleterious recessive alleles.

- **Marker-assisted selection (MAS):** the use of molecular markers linked to target genes or QTLs to select for those loci indirectly, without requiring phenotypic evaluation for the target trait; most effective for qualitative resistance genes and recessive alleles.
- **Mutation breeding:** the deliberate use of physical (gamma rays, X-rays) or chemical (EMS, sodium azide) mutagens to induce new allelic variation in crop populations; most valuable when no natural variation exists for a target trait.
- **Ploidy:** the number of complete chromosome sets present per cell; haploid (n) = one set; diploid (2n) = two sets; tetraploid (4n) = four sets; hexaploid (6n) = six sets.
- **SNP (Single Nucleotide Polymorphism):** a variation at a single nucleotide position in the DNA sequence between individuals; the most abundant type of molecular marker; used in high-throughput genotyping arrays for genomic selection and GWAS.
- **SSR (Simple Sequence Repeat):** a molecular marker consisting of tandem repeats of a short DNA motif (e.g. CA)n; highly polymorphic; co-dominant; widely used for genetic fingerprinting, diversity analysis, and marker-assisted selection.
- **Transgenic crop:** a crop variety into which a gene from another organism has been introduced using genetic transformation; examples include Bt cowpea (Nigeria, approved 2021) expressing a Bacillus thuringiensis insecticidal protein.

Concept Check Questions [Series 2]

Objective Questions

1. An organism with two complete sets of chromosomes from two different parental species, formed by interspecific hybridisation followed by chromosome doubling, is called an _____. (Linked to SLO 2.2)
2. The production of seeds without fertilisation, in which the embryo is genetically identical to the mother, is called _____. (Linked to SLO 2.4)
3. The chemical _____ inhibits spindle formation during mitosis and is used to induce chromosome doubling in plant cells for polyploidy breeding. (Linked to SLO 2.5)

4. Marker-assisted selection uses molecular markers _____ to target genes to select for those genes without direct phenotypic evaluation. (Linked to SLO 2.6)
5. Bt cowpea, expressing the Cry1Ab insecticidal protein, was approved for commercial cultivation in Nigeria by _____ and NAFDAC in 2021. (Linked to SLO 2.6)

Short-Answer Questions

6. Explain the significance of meiosis for plant and animal breeders. (Linked to SLO 2.1)
7. Distinguish between self-pollinating and cross-pollinating crops, give two examples of each, and state one appropriate breeding method for each group. (Linked to SLO 2.3)
8. Explain how colchicine is used to produce an allotetraploid from a sterile interspecific hybrid. (Linked to SLO 2.5)
9. Define genomic selection and state two advantages over traditional progeny testing in livestock breeding. (Linked to SLO 2.6)
10. Describe how CRISPR-Cas9 works and give one crop application relevant to Nigeria. (Linked to SLO 2.6)

Long-Answer Questions

11. Describe the cytogenetic basis of breeding, covering chromosome structure, the significance of meiosis, and the breeding consequences of chromosome aberrations. (Linked to SLOs 2.1, 2.2)
12. Explain the breeding implications of self-pollination and cross-pollination. Describe apomixis and vegetative reproduction and their applications in Nigerian crop improvement. (Linked to SLOs 2.3, 2.4)
13. Describe polyploidy, mutation breeding, and molecular tools (MAS, genomic selection, genetic transformation) and explain their applications in Nigerian plant and animal breeding. (Linked to SLOs 2.5, 2.6)

Answers to Concept Check Questions [Series 2]

Objective Questions

1. Amphidiploid (allopolyploid).

2. Apomixis.
3. Colchicine.
4. Linked.
5. NBMA.

Short-Answer Questions

6. Meiosis generates haploid gametes, enabling fertilisation to restore the diploid state. Crossing-over during meiotic prophase I creates recombinant chromosomes, producing new allele combinations that breeders select from in segregating populations. Independent assortment generates additional variation. In polyploid crops, abnormal multivalent formation during meiosis causes irregular segregation and reduced fertility, which breeders must account for in cross design and progeny evaluation.
7. Self-pollinating crops: rice and cowpea; they are naturally inbred, homozygous, and breed true; suited to pedigree selection and backcross breeding. Cross-pollinating crops: maize and cassava; they are naturally heterozygous; inbreeding causes inbreeding depression; suited to hybrid breeding and recurrent selection.
8. A sterile F1 hybrid between two different species has one chromosome set from each parent and cannot pair homologues at meiosis, making it infertile. Treating shoot meristems or seedlings with colchicine (applied as a solution or paste) blocks spindle formation during mitosis, preventing chromosome separation and doubling the chromosome number. The resulting amphidiploid has two complete sets from each parental species, enabling normal bivalent pairing at meiosis and restoring fertility.
9. Genomic selection predicts an individual's GEBV from thousands of genome-wide SNP markers trained on a reference population. Two advantages over traditional progeny testing: (1) selection can be made at a young age (before phenotypic records are available), shortening the generation interval; (2) it is more accurate for low-heritability traits because it captures the combined effect of all QTLs genome-wide.
10. CRISPR-Cas9 uses a short guide RNA (gRNA) complementary to the target DNA sequence to direct the Cas9 nuclease to make a double-strand break at that locus. The cell repairs the break, often introducing small insertions or deletions that disrupt gene function. Nigerian application: editing the SWEET gene promoter in cassava to prevent

binding of the Xanthomonas pathogen transcription activator, conferring resistance to cassava bacterial blight without introducing foreign DNA.

Long-Answer Questions

11. Chromosomes are DNA-protein structures; ploidy (diploid 2n, tetraploid 4n, hexaploid 6n) determines inheritance patterns. Mitosis produces identical daughter cells; meiosis produces haploid gametes and generates variation via crossing-over and independent assortment. Chromosome aberrations: aneuploids (monosomic 2n-1; trisomic 2n+1) are used to assign genes to chromosomes; structural aberrations (deletions, inversions, translocations) reduce fertility but translocations can transfer resistance genes from wild relatives to crops (e.g. rye-wheat 1BL/1RS translocation carrying stem rust resistance).
12. Self-pollinating crops (rice, wheat, cowpea, groundnut) are naturally homozygous; they breed true; inbreeding depression is minimal; pedigree selection and single seed descent are appropriate methods. Cross-pollinating crops (maize, cassava, pearl millet) are naturally heterozygous; inbreeding exposes deleterious recessives causing inbreeding depression; hybrid breeding and recurrent selection are appropriate. Vegetative reproduction (cassava stem cuttings; yam tuber sets; banana suckers) fixes superior clonal genotypes for distribution to farmers. Apomixis (Panicum maximum; Brachiaria spp.) produces seeds genetically identical to the mother; if transferred to maize or cassava it would allow hybrid seed to be saved and replanted, eliminating annual hybrid seed purchase costs for Nigerian smallholders.
13. Autopolyploidy (same genome doubled; multivalent meiosis; reduced fertility) vs allopolyploidy (genomes from two species; bivalent meiosis; normal fertility; Nigerian examples: groundnut AABB; cassava; cotton AADD; wheat AABBDD). Colchicine induces polyploidy by blocking spindle formation; used to restore fertility in sterile interspecific hybrids (amphidiploids) and to produce seedless triploid watermelon. Mutation breeding (gamma rays, X-rays, EMS) creates new alleles absent from existing germplasm; sorghum and groundnut mutant varieties released in Nigeria. Molecular tools: SSR markers (co-dominant; fingerprinting; genetic diversity); SNP arrays (genome-wide; basis of GS); MAS selects qualitative resistance genes (CMD2 in cassava; Striga resistance QTLs in cowpea) by genotyping linked markers rather than disease screening; genomic selection (IITA cassava; ILRI trypanotolerant cattle) uses

genome-wide GEBVs to select at young age, doubling genetic gain rate. Genetic transformation (Agrobacterium; biolistics) introduces transgenes: Bt cowpea (Cry1Ab; pod borer resistance; approved Nigeria 2021). CRISPR-Cas9 makes targeted edits without foreign DNA: cassava bacterial blight resistance (SWEET gene editing) under development.

Answers to Pilot Questions [Series 2]

Part 2.1

1. Haploid (n): one chromosome set; gametes; e.g. maize pollen (n = 10). Diploid (2n): two sets; e.g. maize somatic cells (2n = 20). Tetraploid (4n): four sets; e.g. groundnut (2n = 4x = 40).
2. Meiosis is more important because it generates haploid gametes enabling sexual reproduction, and produces new allele combinations through crossing-over and independent assortment; these provide the variation breeders select from. Mitosis only replicates existing genotypes for growth and vegetative propagation.
3. Inversion: a chromosome segment is reversed; suppresses recombination within the inverted region, locking together allele combinations; used to maintain favourable linkage groups in some breeding lines. Translocation: a segment moves between non-homologous chromosomes; used to transfer resistance genes from wild relatives to crop chromosomes (e.g. 1BL/1RS rye-wheat translocation carrying stem rust resistance).
4. Maize: 2n = 20. Cassava: 2n = 36. Groundnut: 2n = 40. Cattle: 2n = 60.
5. Crossing-over during meiotic prophase I exchanges segments between non-sister chromatids of homologous chromosomes, producing recombinant chromosomes carrying new allele combinations not present in either parent. This recombinational variation is the raw material that breeders exploit when selecting superior individuals in segregating F2 and later populations.

Part 2.2

1. Self-pollination: pollen fertilises ovules of the same plant; examples: rice, cowpea. Cross-pollination: pollen from a different plant fertilises ovules; examples: maize, cassava.

2. In cross-pollinating species, many deleterious recessive alleles accumulate in heterozygotes where they are masked by dominant alleles. Forced selfing increases homozygosity, allowing deleterious recessives to pair and be expressed, reducing fitness (inbreeding depression). In naturally self-pollinating species, repeated selfing over evolutionary time has already exposed and purged most deleterious recessives, so inbreeding depression is minimal.
3. Dioecy (separate male and female plants): papaya. Monoecy with spatial separation: maize (tassel at apex, silk at ear). Dichogamy (pollen shed and stigma receptivity at different times): avocado. Self-incompatibility (biochemical pollen rejection): most Brassica species.
4. Cassava and yam are propagated through stem cuttings and tuber sets, respectively. Once a breeder identifies a superior genotype with high yield, disease resistance, and good quality through selection or hybridisation, vegetative propagation multiplies exact genetic copies of that individual for distribution to farmers. There is no loss of the superior genotype due to segregation in subsequent generations, unlike seed-propagated crops.
5. Apomixis is seed production without fertilisation; the embryo is genetically identical to the mother. If transferred to maize, it would allow hybrid seed to be saved and replanted across generations without losing heterozygosity or hybrid vigour, removing the need for expensive annual hybrid seed purchase; this would make hybrid maize technology economically accessible to resource-poor Nigerian farmers who cannot afford to buy certified seed every season.

Part 2.3

1. Autopolyploidy: genome doubling within one species; AAAA; multivalent meiosis; reduced fertility; example: artificially induced tetraploid banana. Allopolyploidy: hybridisation between two species followed by chromosome doubling; AABB; bivalent meiosis; normal fertility; example: groundnut (Arachis hypogaea; AABB; 2n = 40).
2. Colchicine binds to tubulin and inhibits spindle formation during mitosis; chromosomes replicate but cannot separate to poles; after cell division fails, the resulting cell has double the original chromosome number. Breeding application: a sterile interspecific hybrid (e.g. cassava x wild Manihot) has one set from each parent and cannot pair

homologues; colchicine treatment doubles the chromosome number to AABB, enabling bivalent meiosis and restoring fertility to produce an amphidiploid useful as a bridge for gene transfer.

3. Mutation breeding uses physical or chemical agents to induce random heritable changes in DNA, creating new alleles not present in the gene pool. Physical mutagen: gamma rays from cobalt-60 (ionising radiation causing DNA double-strand breaks). Chemical mutagen: ethyl methanesulphonate EMS (alkylates guanine; causes G:C to A:T point mutations).
4. Triploid plants (3n) arise by crossing a tetraploid (4n) with a diploid (2n); the resulting triploid has an odd number of chromosome sets and cannot form normal bivalents at meiosis, leading to highly irregular segregation and failure to produce viable seeds. Triploid watermelon is seedless because the irregular meiosis prevents seed formation; the fruit develops normally due to pollination by a diploid polleniser stimulating fruit growth without seed set.
5. Advantages: larger cell size and organ size (gigas effect) in autopolyploids; allopolyploids combine useful genes from two species and may show greater adaptability. Disadvantages: autopolyploids have reduced fertility due to multivalent formation; polyploid genomes are more complex to analyse genetically and breeding cycles may be longer due to more complex segregation patterns.

Part 2.4

1. SSR (microsatellite): multi-allelic (many alleles per locus); co-dominant (heterozygotes distinguishable); moderately abundant; genotyped by PCR and gel/capillary electrophoresis; advantage: high informativeness per locus for diversity and fingerprinting. SNP: most abundant marker type in any genome; suitable for high-throughput chip-based genotyping of thousands to hundreds of thousands of loci simultaneously; advantage: enables genome-wide coverage needed for genomic selection and GWAS.
2. MAS uses a small number of markers (1 to 20) tightly linked to specific known genes or QTLs to select for those loci; best for qualitative resistance genes (CMD2 in cassava; Striga resistance in cowpea) and recessive alleles not visible in heterozygotes. GS uses

thousands of genome-wide SNPs to predict overall breeding value; best for quantitative traits with low heritability (yield, milk production) where many QTLs of small effect cannot be individually identified and selected.

3. Bt cowpea was developed by IITA and IAR (Zaria) in collaboration with the African Agricultural Technology Foundation (AATF) by introducing the Bacillus thuringiensis Cry1Ab gene into elite Nigerian cowpea varieties using Agrobacterium-mediated transformation; the transgene expresses a protein toxic to the pod borer Maruca vitrata. After multi-season confined field trials and safety evaluation, it was approved by the National Biosafety Management Agency (NBMA) and NAFDAC in 2021.
4. CRISPR-Cas9 uses a programmable guide RNA complementary to the target DNA sequence to direct the Cas9 nuclease to make a double-strand break at that locus; the cell's repair machinery introduces small insertions or deletions (indels) that can knock out a gene, or a repair template can be provided for precise sequence changes. Nigerian application: editing the SWEET gene promoter in cassava to block binding of the Xanthomonas bacterial transcriptional activator, preventing upregulation of sugar transport and conferring resistance to cassava bacterial blight without introducing any foreign DNA.
5. In traditional progeny testing, a bull must first have daughters that reach milk production age (approximately 2 to 3 years), then daughters must complete a full lactation (approximately 1 year); the total time from bull birth to selection decision is approximately 5 to 6 years. With genomic selection, a blood or hair sample from the bull calf is genotyped at 6 months of age; the GEBV is calculated from the genome-wide SNP profile; the bull can be selected and its semen used immediately. This reduces the generation interval from 5 to 6 years to under 1 year for the sire path, approximately doubling the annual rate of genetic gain.

References and Attributions [Series 2]

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Figure 2.1: Origins and meiotic behaviour of autopolyploids versus allopolyploids. Attribution: AI generated. Suggested OER search string: “autopolyploidy allopolyploidy origin meiosis comparison diagram crop examples OER”.
- Box 2.1: Comparison of molecular breeding tools and their applications in Nigerian crop and livestock improvement. Attribution: AI generated. Suggested OER search string: “molecular breeding tools MAS genomic selection CRISPR transformation comparison table OER”.

Course code: BIO 402

Course title: Principles of Plant and Animal Breeding

Course credit load: 2 Units

Series 3: Heterosis, Inbreeding, Incompatibility, and Sterility

- **Part 3.1: Heterosis and Its Exploitation**
  - Sub Part 3.1.1: Definition and types of heterosis
  - Sub Part 3.1.2: Genetic bases of heterosis
  - Sub Part 3.1.3: Exploitation of heterosis in crop and livestock improvement
- **Part 3.2: Inbreeding and Its Consequences**
  - Sub Part 3.2.1: Definition and measurement of inbreeding
  - Sub Part 3.2.2: Inbreeding depression: causes and manifestations
  - Sub Part 3.2.3: Useful applications of inbreeding in breeding programmes
- **Part 3.3: Incompatibility Mechanisms**
  - Sub Part 3.3.1: Self-incompatibility: types and mechanisms
  - Sub Part 3.3.2: Interspecific incompatibility and pre-fertilisation barriers
  - Sub Part 3.3.3: Overcoming incompatibility in breeding
- **Part 3.4: Sterility in Plant and Animal Breeding**
  - Sub Part 3.4.1: Types of sterility in plants
  - Sub Part 3.4.2: Cytoplasmic male sterility and its use in hybrid seed production
  - Sub Part 3.4.3: Sterility in animals: causes and management

Introduction

Heterosis, inbreeding, incompatibility, and sterility are four closely connected phenomena that together determine the genetic architecture of breeding populations and the strategies available to improve them. Heterosis (hybrid vigour) is the superior performance of hybrids over their parents; exploiting it has delivered some of the largest yield gains in crop and livestock improvement. Inbreeding is the mating of related individuals; it increases homozygosity, may cause inbreeding depression, and is both a tool and a hazard in breeding. Incompatibility prevents fertilisation between genetically incompatible pollen and pistil or between different species; it is both an obstacle and a tool. Sterility, whether in plants or animals, impairs reproduction but certain forms are deliberately exploited in hybrid seed production and controlled mating systems.

This Series covers the mechanisms, genetic bases, consequences, and breeding applications of all four phenomena. The concepts apply to both plant and animal breeding, though the specific systems differ between crops and livestock. Understanding these topics is essential for designing hybrid variety programmes, managing inbreeding in small populations, exploiting male sterility for seed production, and diagnosing and managing fertility problems in Nigerian farm animals.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 3.1** define heterosis, describe its types and genetic bases, and explain how it is exploited in crop and livestock improvement (Linked to Part 3.1),
- **SLO 3.2** define inbreeding, measure it using the inbreeding coefficient, and explain the causes and consequences of inbreeding depression (Linked to Part 3.2),
- **SLO 3.3** describe useful applications of inbreeding in plant and animal breeding programmes (Linked to Part 3.2),
- **SLO 3.4** explain self-incompatibility and interspecific incompatibility mechanisms and describe methods used to overcome incompatibility barriers (Linked to Part 3.3),

- **SLO 3.5** describe the types of sterility in plants, explain cytoplasmic male sterility (CMS), and show how CMS is used in hybrid seed production (Linked to Part 3.4), and
- **SLO 3.6** describe the causes and management of sterility in farm animals (Linked to Part 3.4).

3.1 Heterosis and Its Exploitation

3.1.1 Definition and types of heterosis

Heterosis (hybrid vigour) is the phenomenon in which the F1 hybrid offspring of two genetically different parents exhibits superior performance relative to one or both parents for one or more traits. It is quantified as: mid-parent heterosis (MPH) = (F1 mean – mid-parent mean) / mid-parent mean x 100; or better-parent heterosis (BPH) = (F1 mean – better parent mean) / better parent mean x 100. BPH is the more commercially important measure because it indicates that the hybrid outperforms the best available parent. Traits that show the greatest heterosis are generally fitness-related, lowly heritable traits such as grain yield, growth rate, litter size, disease resistance, and reproductive efficiency.

Types of heterosis include: individual heterosis (the F1 individual itself performs better than its parents; most relevant for livestock and hybrid crop varieties); maternal heterosis (the performance of offspring is enhanced by the heterozygosity of the dam; important for litter size and milk yield in pigs and cattle); paternal heterosis (enhanced performance due to sire heterozygosity; less common). In plants, specific combining ability (SCA) measures the heterosis expressed in a specific cross between two defined parents, beyond that predicted by their general combining ability (GCA). Crosses with high SCA are the basis of commercial hybrid varieties in maize, sorghum, sunflower, and rice.

Fill in the blank: Better-parent heterosis (BPH) measures the superiority of the F1 hybrid over the _____ parent; it is more commercially important than mid-parent heterosis because it shows that the hybrid outperforms the best currently available variety.

3.1.2 Genetic bases of heterosis

Three genetic hypotheses explain heterosis. The dominance hypothesis proposes that at many loci, the heterozygote (Aa) performs at least as well as the dominant homozygote (AA) and better than the recessive homozygote (aa); when two inbred lines each carrying different sets of deleterious recessive alleles are crossed, the F1 hybrid has all deleterious recessives complemented by dominant alleles from the other parent, resulting in superior performance. The overdominance hypothesis proposes that the heterozygote (Aa) at certain loci is intrinsically superior to either homozygote (AA or aa); this is genuine single-locus overdominance. The epistasis hypothesis proposes that favourable allele interactions between loci (epistasis) are more frequent in hybrids than in inbred parents.

Current evidence suggests that dominance complementation is the primary mechanism underlying most heterosis in crops and livestock, with overdominance and epistasis playing supplementary roles. In maize, genome-wide association studies (GWAS) and transcriptomic analyses show that the F1 hybrid is intermediate between parents for most genes but shows non-additive expression (higher or lower than the midparent) at a minority of loci, particularly those involved in growth and stress response. In livestock (pigs, cattle), heterosis for litter size, survival, and growth rate is consistent with the dominance complementation model. Practical implication: to maximise heterosis in a cross, the two parents should be as genetically divergent as possible, so that each parent's deleterious recessives are complemented by dominant alleles from the other parent.

Fill in the blank: The _____ hypothesis for heterosis proposes that the superior performance of F1 hybrids results from complementation of deleterious recessive alleles: each parent's recessive alleles are masked by dominant alleles from the other parent in the heterozygous F1.

3.1.3 Exploitation of heterosis in crop and livestock improvement

In plant breeding, heterosis is exploited through hybrid varieties produced by crossing two genetically distinct, homozygous inbred lines. The steps are: (1) develop inbred lines by repeated selfing of diverse parents; (2) evaluate inbred lines for GCA (performance in crosses with many partners) and SCA (performance in specific crosses); (3) identify the best-combining pairs; (4)

produce F1 hybrid seed commercially by crossing the two parent lines in an isolation block, using either detasselling (in maize), male sterility, or self-incompatibility to prevent self-pollination. In Nigeria, IITA and NCRI release hybrid maize varieties (SAMMAZ hybrids) and hybrid sorghum and pearl millet varieties (IAR, Zaria); hybrid rice varieties are under development. Hybrid varieties require farmers to purchase new seed each season because the F2 generation shows segregation and loses heterosis.

In livestock, heterosis is exploited through crossbreeding: crossing two or more breeds to produce F1 crossbred animals with superior performance for fitness traits. In Nigerian cattle production, crossing White Fulani (local zebu; adapted; low milk yield) with Holstein-Friesian (exotic; high milk) produces F1 crosses with milk yields of 2,000 to 4,000 litres per lactation, far exceeding either pure parent in the Nigerian environment; the F1 also shows heterosis for calf survival rate and reproductive efficiency. In pig production, crossing Nigerian indigenous pigs with Landrace or Large White produces F1 crosses with improved growth rate, feed conversion, and litter size. Rotational crossbreeding systems (two-breed or three-breed rotation) maintain heterosis in commercial livestock production without continuously sourcing pure-breed bulls.

Fill in the blank: In maize hybrid seed production, _____ (removal of the male tassel) from the seed-parent rows prevents self-pollination and forces cross-pollination with the pollen-parent rows; this is one method used to produce F1 hybrid seed in the absence of a male sterility system.

Pilot questions 3.1

1. Define heterosis and distinguish between mid-parent and better-parent heterosis.
2. State the three genetic hypotheses for heterosis and indicate which is most widely supported.
3. Explain how hybrid maize seed is produced in Nigeria and why farmers must buy new seed each season.
4. Describe how heterosis is exploited in Nigerian cattle breeding and state the expected benefit.

5. Explain the difference between general combining ability (GCA) and specific combining ability (SCA).

3.2 Inbreeding and Its Consequences

3.2.1 Definition and measurement of inbreeding

Inbreeding is the mating of individuals that are more closely related to each other than the average relationship within the population. It increases the probability that the two alleles at any locus in an individual are identical by descent (IBD), i.e. copies of the same ancestral allele. The inbreeding coefficient (F) quantifies this probability; F = 0 means no inbreeding (random mating); F = 1 means complete inbreeding (fully homozygous at all loci). F can be calculated from a pedigree using Wright's path coefficient method; it can also be estimated from genome-wide molecular marker data as the proportion of the genome that is homozygous (runs of homozygosity, ROH).

The rate of inbreeding per generation (ΔF) in a randomly mating population is approximately 1/(2Ne), where Ne is the effective population size. A small breeding population (small Ne) accumulates inbreeding rapidly. In cattle herds with only 2 to 3 bulls, Ne may be as low as 8 to 12, and inbreeding can accumulate at 4 to 6 percent per generation. In self-pollinating crops, F increases by 50 percent per generation of selfing; after n generations of selfing, F = 1 – (1/2)^n; after 6 generations, F ≥ 0.98 (near-complete homozygosity). Plant breeders deliberately increase F by selfing to create homozygous inbred lines as parents for hybrid varieties.

Fill in the blank: The inbreeding coefficient (F) measures the probability that the two alleles at any locus in an individual are _____ by descent (IBD); F = 0 indicates no inbreeding and F = 1 indicates complete homozygosity at all loci.

3.2.2 Inbreeding depression: causes and manifestations

Inbreeding depression is the reduction in phenotypic performance (for fitness-related traits) that results from increased homozygosity due to inbreeding. It is caused primarily by the increased

expression of deleterious recessive alleles that are normally masked in heterozygotes in randomly mating populations. As F increases, the frequency of homozygous recessive genotypes (aa) increases, exposing their deleterious effects. A secondary cause is the loss of overdominance benefits at loci where the heterozygote (Aa) is intrinsically superior to either homozygote.

Inbreeding depression is most severe for lowly heritable fitness traits: reproductive rate, survival, immune function, and disease resistance. In maize, inbreeding depression for grain yield is severe; grain yield of S3 inbred lines may be only 20 to 40 percent of the open-pollinated population mean, and highly inbred lines (S6 to S8) show further reductions in vigour, fertility, and resistance to stress. In livestock, inbreeding depression in White Fulani cattle at 10 percent inbreeding has been estimated at 2 to 4 percent reduction in calving rate and 3 to 5 percent reduction in calf survival. In pigs, inbreeding at F = 0.10 reduces litter size by approximately 0.4 to 0.8 piglets per litter. Traits with high heritability (body conformation, carcass composition) show less inbreeding depression than low-heritability traits.

Fill in the blank: Inbreeding depression is most severe for traits with _____ heritability, such as reproductive rate, litter size, and disease resistance, because these traits are most strongly influenced by dominance effects at loci where the heterozygote is superior to the recessive homozygote.

3.2.3 Useful applications of inbreeding in breeding programmes

Despite its negative consequences for fitness traits, inbreeding is deliberately used in several breeding contexts. In plant breeding, inbred lines are developed by repeated selfing (6 to 8 generations) to produce near-homozygous, true-breeding lines that: serve as parents for hybrid variety production (the basis of the hybrid seed industry); allow comparison of lines across environments because their genetic composition is fixed; fix superior allele combinations identified through selection; and enable genetic studies because all plants in an inbred line are genetically identical. IITA develops and maintains hundreds of inbred lines of maize, sorghum, and cowpea for use as hybrid parents or elite varieties.

In animal breeding, moderate inbreeding within elite families is used to fix desirable allele combinations and establish a distinctive genetic type (as in the development of pure breeds from

crossbred founder populations). Linebreeding is a mild form of inbreeding that concentrates the genes of a specific outstanding ancestor without allowing F to rise too high; it is used in cattle and sheep breeding to maintain the genetic influence of a superior bull or ram. Testing for genetic defects (recessive lethal alleles) is facilitated by inbreeding: a carrier sire mated to carrier daughters will produce approximately 25 percent affected offspring, revealing the presence of a recessive defect in the herd. Inbreeding management (avoiding close matings; monitoring F) is critical in small Nigerian cattle herds and conservation breeding programmes for endangered breeds.

Fill in the blank: In plant breeding, near-complete homozygous lines developed by 6 to 8 generations of selfing are called _____ lines; they serve as the parents of commercial hybrid varieties and as stable, true-breeding material for genetic studies.

Pilot questions 3.2

1. Define the inbreeding coefficient (F) and state what F = 0 and F = 1 mean in practice.
2. Explain the primary cause of inbreeding depression and state which types of traits are most affected.
3. Why is inbreeding depression more severe in maize than in cowpea?
4. Describe two useful applications of inbreeding in plant breeding and one in animal breeding.
5. Explain how the effective population size (Ne) determines the rate of inbreeding accumulation in a livestock herd.

3.3 Incompatibility Mechanisms

3.3.1 Self-incompatibility: types and mechanisms

Self-incompatibility (SI) is a genetically controlled mechanism that prevents self-fertilisation and promotes outbreeding in hermaphrodite flowering plants by causing the rejection of self-pollen after it lands on the stigma. SI is widespread: it occurs in over 100 plant families including Solanaceae (potato, tomato relatives), Brassicaceae, Rosaceae, Poaceae, and Asteraceae. There

are two main types. Sporophytic SI (SSI): the pollen grain's incompatibility is determined by the genotype of the sporophytic (diploid, pollen-producing) parent; incompatibility is expressed at the stigma surface immediately after pollen landing; pollen tubes do not form; occurs in Brassica species and some Asteraceae. Gametophytic SI (GSI): the pollen grain's incompatibility is determined by its own haploid genotype; pollen tubes germinate but are arrested in the style; occurs in Solanaceae, Rosaceae, Poaceae.

The molecular basis of SI involves matching between products of the S-locus in both pollen and pistil. In Brassica SSI, S-locus receptor kinase (SRK) in the stigma recognises S-locus cysteine-rich protein (SCR) in the pollen coat; if they match (pollen and pistil share an S-allele), the pistil rejects the pollen. In Solanaceae GSI, the S-RNase in the pistil degrades RNA in incompatible pollen tubes, arresting growth. The practical breeding implication of SI is that it enforces cross-pollination, maintaining heterozygosity and preventing inbreeding; breeders exploit it as a natural hybridisation system in hybrid seed production of Brussels sprouts, cabbage, and oilseed rape (canola), where SI parents can be used without emasculation.

Fill in the blank: In _____ self-incompatibility (SSI), which occurs in Brassica species, the incompatibility reaction is determined by the diploid genotype of the pollen-parent plant; pollen tube germination is prevented immediately at the stigma surface when pollen and pistil share an S-allele.

3.3.2 Interspecific incompatibility and pre-fertilisation barriers

Interspecific incompatibility refers to the failure of fertilisation between individuals of different species, due to pre-fertilisation or post-fertilisation barriers. Pre-fertilisation barriers include: different flowering times (seasonal or diurnal); different pollinator specialisation (a bee-pollinated species and a wind-pollinated species do not exchange pollen); physical barriers (pollen grains too large or too small to germinate on a foreign stigma; incompatible pollen-stigma surface biochemistry); and pollen tube arrest in the style of the foreign species. Post-fertilisation barriers include: failure of embryo development due to endosperm breakdown (endosperm-embryo incompatibility); hybrid lethality; hybrid weakness; or hybrid sterility (F1

hybrids that grow normally but cannot produce gametes due to meiotic irregularities from chromosome number or structural differences).

Interspecific incompatibility is a major obstacle in wide hybridisation, which is the crossing of cultivated species with related wild species or distant relatives to transfer genes not present in the cultivated gene pool. Examples in Nigerian crops: cassava breeders at IITA attempt wide crosses between Manihot esculenta (cultivated cassava; 2n = 36) and wild Manihot species such as M. glaziovii (2n = 36) or M. dichotoma (2n = 36) to transfer resistance to cassava mosaic disease and cassava brown streak disease; the crosses are partially compatible but embryo rescue is often needed to recover hybrids. Wide crosses between cultivated groundnut (Arachis hypogaea; allotetraploid; 2n = 40) and diploid wild Arachis species require embryo rescue and chromosome doubling to produce fertile amphidiploids at ICRISAT-Nigeria and IAR Zaria.

Fill in the blank: The crossing of a cultivated crop species with a related wild species to transfer genes absent from the cultivated gene pool is called _____ hybridisation; it is used in cassava breeding at IITA to transfer disease resistance from wild Manihot species to cultivated cassava.

3.3.3 Overcoming incompatibility in breeding

Several techniques are used to overcome self-incompatibility or interspecific incompatibility barriers. Bud pollination overcomes GSI by pollinating the bud before the SI mechanism is fully active (stigma SI is not yet expressed in immature buds). Mentor pollen technique: compatible pollen (killed by heat or irradiation) is mixed with incompatible pollen; the compatible pollen provides factors that help incompatible pollen tubes penetrate the style (used in apple and pear breeding). CO2 treatment and high temperature treatments temporarily suppress SI, allowing self-fertilisation to produce homozygous plants needed for hybrid parent development.

For interspecific crosses, techniques include: embryo rescue (excising the developing hybrid embryo before it aborts and culturing it on artificial medium in vitro; widely used at IITA for wide cassava crosses and at IAR for wide Arachis crosses); bridge crosses (crossing the incompatible pair via a third species that is compatible with both); chromosome doubling of the sterile F1 hybrid with colchicine to produce a fertile amphidiploid; and in vitro pollen tube culture. In animal breeding, species barriers between cattle and buffalo, or between domestic

cattle and wild bison, have been partially overcome using embryo transfer and in vitro fertilisation techniques to produce interspecific hybrids.

Fill in the blank: _____ rescue involves excising a developing hybrid embryo before it aborts and culturing it on artificial medium; it is widely used at IITA in wide crosses between Manihot esculenta and wild Manihot species to recover hybrids that would otherwise be lost due to endosperm breakdown.

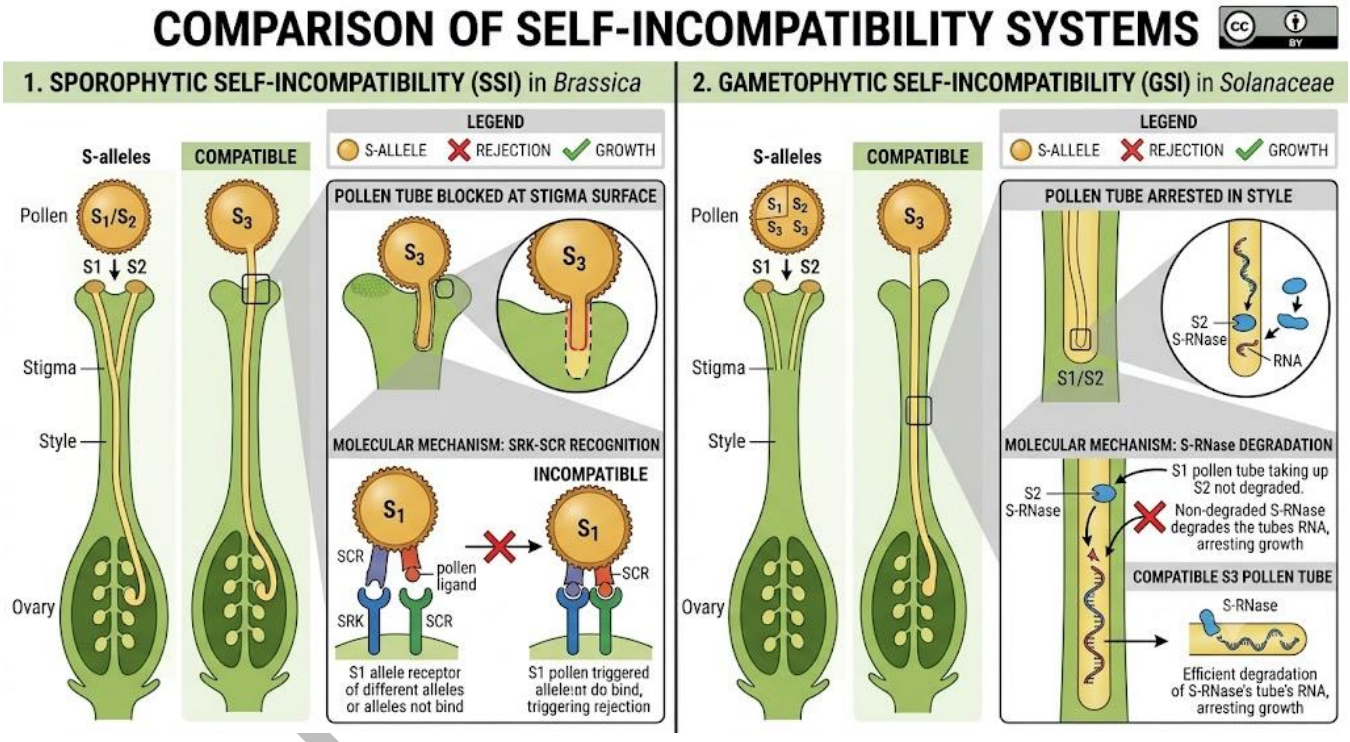

Figure 3.1: Mechanisms of sporophytic (SSI) and gametophytic (GSI) self-incompatibility

Pilot questions 3.3

1. Distinguish between sporophytic and gametophytic self-incompatibility and give one crop example of each.
2. Explain the molecular basis of self-incompatibility in Brassica species.
3. Define interspecific incompatibility and distinguish between pre-fertilisation and post-fertilisation barriers.
4. Describe two techniques used to overcome interspecific incompatibility in wide hybridisation programmes.

5. How is self-incompatibility exploited in hybrid seed production of Brassica crops?

3.4 Sterility in Plant and Animal Breeding

3.4.1 Types of sterility in plants

Sterility in plants refers to the failure to produce functional pollen (male sterility) or viable ovules/seeds (female sterility), or both. Male sterility is far more common and breeding-relevant than female sterility. Types of male sterility: (1) Genetic (nuclear) male sterility (GMS): caused by recessive nuclear genes (ms/ms genotype); plants with ms/ms produce non-functional pollen; maintained by crossing ms/ms (sterile) x Ms/ms (heterozygous fertile) which gives 50 percent sterile progeny; used in some hand-pollinated crops. (2) Cytoplasmic male sterility (CMS): caused by incompatibility between the mitochondrial genome (cytoplasm) and the nuclear genome; not mendelian; maternally inherited; all progeny of a CMS female are sterile unless a restorer gene (Rf) is present in the pollen parent. (3) Cytoplasmic-genic male sterility (CGMS): the most useful system; combines CMS cytoplasm with nuclear restorer genes; the basis of hybrid seed production in maize, sorghum, rice, pearl millet, and sunflower.

Structural sterility arises from chromosome imbalance (polyploids or hybrids with odd ploidy or chromosome translocations that cause irregular meiosis). Functional sterility occurs when pollen is structurally normal but physiologically non-viable due to temperature extremes, drought, or nutrient deficiency at anthesis. Ethephon (ethylene-releasing compound) and gametocides (chemical hybridising agents such as sodium methyl arsenate, SMA; maleic hydrazide) can induce temporary male sterility for hybrid seed production in crops lacking natural sterility systems. Understanding the type of sterility present is essential before designing a hybrid seed production system.

Fill in the blank: _____ male sterility is caused by incompatibility between the mitochondrial genome and the nuclear genome; it is maternally inherited and not governed by Mendelian ratios; it is the basis of the three-line hybrid seed production system in rice, sorghum, and maize.

3.4.2 Cytoplasmic male sterility and its use in hybrid seed production

The CMS-based three-line hybrid seed production system uses three lines: the A-line (CMS line; male sterile; cms cytoplasm; ms/ms nuclear genotype; the seed parent); the B-line (maintainer line; normal cytoplasm; ms/ms nuclear genotype; genetically identical to A-line except for cytoplasm; used to maintain the A-line by crossing B x A, producing A-line seed); and the R-line (restorer line; CMS cytoplasm or normal cytoplasm; carries dominant restorer gene Rf/Rf or Rf/rf; used as pollen parent; Rf restores pollen fertility in F1 hybrid). The commercial hybrid is produced by crossing A (seed parent) x R (pollen parent) in an isolation block; the F1 hybrid inherits CMS cytoplasm from the A-line but also inherits Rf from the R-line, restoring its own fertility.

Three-line CMS hybrid systems are operational in Nigeria for: sorghum (IAR Zaria; uses Milo-CMS cytoplasm); pearl millet (IAR Zaria; uses Tift 23A CMS source); and rice (NCRI Badeggi; using WA-CMS system developed by IRRI). For maize, which has a CMS system (Texas T-cytoplasm), the primary hybridisation method in Nigeria is detasselling of seed-parent rows combined with selection for CGMS. The two-line system (using photoperiod-sensitive or thermo-sensitive genic male sterility, PGMS or TGMS, as the seed parent) is used in some rice hybrid programmes; it is simpler (requires only two lines) but dependent on specific environmental conditions to trigger sterility. Hybrid seed production is a technically demanding operation that requires strict isolation distances, synchronised flowering of the parent lines, and rigorous roguing of off-types.

Fill in the blank: In the three-line hybrid seed production system, the _____ line (maintainer line) has normal cytoplasm and the same nuclear genotype as the A-line (ms/ms); it is crossed with the A-line each season to produce more A-line seed without restoring fertility.

3.4.3 Sterility in animals: causes and management

Sterility in farm animals is the complete inability to reproduce; subfertility is reduced reproductive efficiency. Both are economically significant in Nigerian livestock production. Causes in females include: anatomical abnormalities (freemartinism in female cattle born co-twin with a male calf; failure of normal reproductive tract development due to masculinising

hormones from the male twin; approximately 90 percent of freemartins are sterile); nutritional deficiencies (energy deficit causing anoestrus; vitamin A or E deficiency impairing ovarian function); infectious diseases (brucellosis, Brucella abortus; Campylobacter fetus causing early embryo death and repeat breeding; Trichomonas foetus in cattle; Newcastle disease reducing egg production in poultry); hormonal imbalances (ovarian cysts; persistent corpus luteum; failure of ovulation); and genetic defects.

Causes of sterility in males include: anatomical defects (cryptorchidism: failure of testes to descend into the scrotum; hypoplasia of testes); poor semen quality (low motility, morphological abnormalities, low concentration); environmental stressors (heat stress in taurine bulls and exotic breeds in Nigeria's humid south; scrotal hyperthermia from tick burden); diseases (contagious equine metritis; bovine viral diarrhoea); and nutritional deficiency. Management of sterility in Nigerian livestock includes: regular breeding soundness evaluation (BSE) of bulls and rams before the mating season; vaccination against brucellosis and other reproductive diseases; nutritional management to maintain body condition score; introduction of genetically superior bulls from AI centres; and culling of confirmed sterile or sub-fertile animals.

Fill in the blank: _____ is a condition in female cattle born as co-twins with male calves; approximately 90 percent of such females are sterile because masculinising hormones from the male foetus pass through the shared placental circulation and disrupt normal development of the female reproductive tract.

Line Name	Cytoplasm Type	Nuclear Genotype	Role in System	Nigerian Crop Example
A Line (CMS Female)	Sterile cytoplasm	Male-sterile nuclear genotype	Provides female parent for hybrid seed production	Rice CMS lines used at NCRI Badeggi
B Line (Maintainer)	Normal fertile cytoplasm	Identical nuclear genotype to A line	Maintains A line by backcrossing, ensures CMS stability	Maintainer lines in rice breeding programs

R Line (Restorer)	Normal fertile cytoplasm	Fertile nuclear genotype with restorer genes (Rf)	Restores fertility in A line hybrids	Sorghum restorer lines used at IAR Zaria
F1 Hybrid	Sterile cytoplasm from A line	Fertile nuclear genotype from R line	Commercial hybrid seed with restored fertility	Hybrid rice and sorghum varieties in Nigerian trials

Box 3.1: Three-line CMS hybrid seed production system with Nigerian sorghum example

Pilot questions 3.4

1. Distinguish between genetic (nuclear) male sterility and cytoplasmic male sterility (CMS).
2. Describe the three lines of the CMS hybrid seed production system and state the role of each.
3. Name two crops in Nigeria where CMS-based hybrid seed production systems are used.
4. State four causes of female sterility in Nigerian cattle and one management measure for each.
5. Explain what freemartinism is and state its genetic basis.

Series Summary

Heterosis is the superior performance of F1 hybrids relative to their parents; measured as mid-parent or better-parent heterosis. It is greatest for lowly heritable fitness traits. The primary genetic basis is dominance complementation; overdominance and epistasis are secondary. Heterosis is exploited through hybrid varieties in crops (maize, sorghum, pearl millet; IITA and IAR hybrids in Nigeria) and crossbreeding in livestock (White Fulani x Holstein-Friesian; Landrace x Large White pig). Inbreeding (mating of related individuals) increases homozygosity;

quantified by the inbreeding coefficient F. Inbreeding depression is caused by expression of deleterious recessives at fitness loci; most severe for low-heritability traits (reproductive rate, litter size). Inbreeding is deliberately used to develop homozygous inbred lines as hybrid parents in plant breeding and to fix traits in animal breeds.

Self-incompatibility (SI) prevents self-fertilisation: sporophytic SI (Brassica; SRK-SCR; pollen blocked at stigma) and gametophytic SI (Solanaceae; S-RNase; tube arrested in style). SI is exploited in hybrid Brassica seed production without emasculation. Interspecific incompatibility (pre- and post-fertilisation barriers) limits wide hybridisation; overcome by embryo rescue, bridge crosses, and chromosome doubling. Plant sterility types include GMS (nuclear recessive), CMS (mitochondrial-nuclear incompatibility; maternally inherited), and structural sterility. The three-line CMS system (A-line seed parent; B-line maintainer; R-line restorer) is used for sorghum and pearl millet hybrid production at IAR Zaria and rice at NCRI Badeggi. Animal sterility causes include freemartinism, brucellosis, nutritional deficiency, cryptorchidism, and heat stress; management includes BSE, vaccination, and nutritional support.

Glossary of Terms

- **Better-parent heterosis (BPH):** the superiority of the F1 hybrid over the better of the two parents, expressed as a percentage; the commercially relevant measure of hybrid vigour.
- **Bridge cross:** a three-way cross using a third species that is compatible with both target species to transfer genes between two otherwise incompatible species.
- **Cytoplasmic male sterility (CMS):** male sterility caused by incompatibility between the mitochondrial genome (cytoplasm) and the nuclear genome; maternally inherited; the basis of three-line hybrid seed production in sorghum, pearl millet, and rice.
- **Dominance hypothesis:** the explanation of heterosis based on complementation of deleterious recessive alleles: each parent's recessives are masked by dominant alleles from the other parent in the F1 heterozygote.

- **Embryo rescue:** the in vitro culture of excised hybrid embryos to prevent abortion; used in wide crosses between incompatible species such as Manihot esculenta x wild Manihot species at IITA.
- **Freemartinism:** sterility in female cattle born as co-twins with male calves; caused by hormonal transfer from male to female foetus through shared placental blood vessels; approximately 90 percent of freemartins are infertile.
- **Gametophytic self-incompatibility (GSI):** self-incompatibility in which the pollen grain's compatibility is determined by its own haploid genotype; pollen tube enters the style but is arrested by S-RNase in incompatible pistils; occurs in Solanaceae and Poaceae.
- **General combining ability (GCA):** the average performance of a line or breed in crosses with many different partners; determined primarily by additive gene effects; used to identify parents with broadly good performance across many crosses.
- **Heterosis:** the superior performance of F1 hybrid offspring relative to one or both parents for one or more traits; also called hybrid vigour; greatest for fitness-related, lowly heritable traits.
- **Inbreeding coefficient (F):** the probability that the two alleles at any locus in an individual are identical by descent; F = 0 in random mating; F = 1 in complete homozygosity; increases with relatedness of mating partners.
- **Inbreeding depression:** the reduction in performance for fitness-related traits caused by increased homozygosity from inbreeding; primarily due to expression of deleterious recessive alleles previously masked in heterozygotes.
- **Inbred line:** a plant line developed by 6 to 8 generations of self-pollination; near-completely homozygous; used as parents for hybrid variety production and as genetically stable material for research.
- **Overdominance hypothesis:** the hypothesis that the heterozygote (Aa) at certain loci is intrinsically superior to both homozygotes (AA and aa); invoked as a supplementary explanation for heterosis at specific loci.

- **Specific combining ability (SCA):** the deviation of a cross's performance from that predicted by the GCAs of its parents; high SCA indicates that the two parents combine particularly well for heterosis; determined largely by non-additive gene effects.
- **Sporophytic self-incompatibility (SSI):** self-incompatibility in which the pollen's compatibility is determined by the diploid sporophyte genotype; rejection occurs at the stigma surface; occurs in Brassica species.

Concept Check Questions [Series 3]

Objective Questions

1. Better-parent heterosis measures the F1 hybrid's superiority over the _____ parent; it is the commercially relevant measure of hybrid vigour. (Linked to SLO 3.1)
2. The primary genetic hypothesis explaining most heterosis is the _____ hypothesis, based on complementation of deleterious recessive alleles. (Linked to SLO 3.1)
3. The inbreeding coefficient (F) measures the probability that the two alleles at a locus are identical by _____; F = 1 indicates complete homozygosity. (Linked to SLO 3.2)
4. In the CMS three-line hybrid system, the _____ line has normal cytoplasm and ms/ms nuclear genotype and is used to maintain the A-line. (Linked to SLO 3.5)
5. Female cattle born co-twin with a male calf and rendered infertile by masculinising hormones from the male twin are called _____. (Linked to SLO 3.6)

Short-Answer Questions

- Explain why heterosis is greatest for traits with low heritability. (Linked to SLO 3.1)
- Describe how inbred lines are developed for use as hybrid parents in maize breeding. (Linked to SLO 3.3)
- Distinguish between sporophytic and gametophytic self-incompatibility. (Linked to SLO 3.4)
- Describe the three lines of the CMS hybrid seed production system and state the role of each. (Linked to SLO 3.5)

- State three causes of male sterility in Nigerian farm animals and one management measure for each. (Linked to SLO 3.6)

Long-Answer Questions

1. Explain heterosis, its genetic bases, and how it is exploited in Nigerian crop and livestock improvement. (Linked to SLOs 3.1)
2. Explain inbreeding, the inbreeding coefficient, and inbreeding depression. Describe two applications of inbreeding in plant breeding and one in animal breeding. (Linked to SLOs 3.2, 3.3)
3. Describe self-incompatibility and interspecific incompatibility mechanisms. Explain how CMS is used in hybrid seed production in Nigeria. (Linked to SLOs 3.4, 3.5)

Answers to Concept Check Questions [Series 3]

Objective Questions

6. Better.
7. Dominance.
8. Descent.
9. B.
10. Freemartins.

Short-Answer Questions

11. Low-heritability traits are strongly influenced by non-additive genetic effects (dominance and epistasis). In hybrids, dominance complementation is maximised because each parent's deleterious recessives are masked by the other parent's dominant alleles; this complementation contributes most to trait performance when additive effects are relatively small, making the non-additive heterotic component the dominant source of hybrid superiority.
12. Select divergent parents from different genetic backgrounds; self each parent plant for 6 to 8 generations to fix near-complete homozygosity ($F \geq 0.98$); evaluate inbred lines for yield per se and in testcrosses to assess GCA; identify pairs with high SCA in diallel or

line x tester crosses; use selected pairs as A-line (seed parent) and R-line (pollen parent) in hybrid seed production.

13. SSI (Brassica): incompatibility determined by the diploid sporophyte genotype; pollen tube blocked at stigma surface via SRK-SCR protein recognition; one S-allele shared between pollen and pistil triggers rejection. GSI (Solanaceae): incompatibility determined by the haploid pollen genotype; pollen tube germinates and enters the style but is arrested by S-RNase which degrades RNA in the incompatible tube.
14. A-line (CMS line): cms cytoplasm; ms/ms nuclear genotype; male sterile; used as seed parent in hybrid production. B-line (maintainer): normal cytoplasm; ms/ms nuclear genotype; crossed with A-line to produce A-line seed each season without restoring fertility. R-line (restorer): carries dominant Rf gene; used as pollen parent; Rf restores pollen fertility in the F1 hybrid.
15. Cryptorchidism (undescended testes): manage by culling affected males from breeding programme. Heat stress (scrotal hyperthermia in exotic breeds): house bulls in shaded, ventilated facilities; use locally adapted or crossbred bulls. Brucellosis (Brucella abortus causing epididymitis and poor semen quality): vaccinate females; test and cull seropositive males.

Long-Answer Questions

1. Heterosis: F1 hybrid outperforms parents; MPH = (F1 - midparent)/midparent x 100; BPH = (F1 - better parent)/better parent x 100; greatest for fitness traits (grain yield, litter size, survival). Genetic bases: dominance (complementation of deleterious recessives; primary mechanism); overdominance (heterozygote superior at specific loci; secondary); epistasis (favourable allele interactions; supplementary). Exploitation in crops: develop inbred lines by selfing; assess GCA and SCA; produce F1 hybrid seed by crossing A-line x R-line using CMS or detasselling; IITA/NCRI SAMMAZ hybrid maize; IAR hybrid sorghum and pearl millet. Exploitation in livestock: crossbreeding White Fulani x Holstein-Friesian for milk yield heterosis; Landrace x Large White pig for litter size; rotational crossbreeding maintains heterosis across generations.
2. Inbreeding: mating of related individuals; increases homozygosity; F = probability both alleles are IBD; F = 1 - (1/2)^n after n selfing generations; ΔF = 1/(2Ne) per generation in

random mating. Inbreeding depression: expression of deleterious recessives; most severe for low-heritability traits; maize yield drops to 20 to 40 percent of OP mean in S3 inbreds; White Fulani cattle at F = 0.10 lose 2 to 4 percent calving rate. Applications in plant breeding: (1) develop homozygous inbred lines for hybrid variety production (IITA maize inbreds); (2) fix superior allele combinations in elite varieties. Application in animal breeding: linebreeding concentrates genes of outstanding ancestor; moderate inbreeding establishes pure breed characteristics; reveals recessive defects via test matings.

3. Self-incompatibility: SSI (Brassica; SRK-SCR; rejection at stigma; exploited in hybrid Brassica seed production without emasculation); GSI (Solanaceae, Poaceae; S-RNase arrests pollen tube in style). Interspecific incompatibility: pre-fertilisation (different flower timing; pollen-stigma biochemical incompatibility); post-fertilisation (endosperm breakdown; hybrid lethality; hybrid sterility). Overcome by: embryo rescue (IITA cassava x wild Manihot; IAR groundnut x wild Arachis); bridge crosses; colchicine chromosome doubling to restore amphidiploid fertility. CMS hybrid production: A-line (cms; sterile; seed parent); B-line (normal cytoplasm; maintains A-line); R-line (carries Rf; restores F1 fertility; pollen parent). Commercial hybrid = A x R; F1 inherits cms cytoplasm and Rf, so it is fertile. Nigerian examples: sorghum and pearl millet hybrids at IAR Zaria; rice hybrids at NCRI Badeggi using WA-CMS.

Answers to Pilot Questions [Series 3]

Part 3.1

6. Heterosis: superior performance of F1 hybrid relative to parents. MPH = (F1 - midparent mean)/midparent x 100; measures superiority over average of both parents. BPH = (F1 - better parent)/better parent x 100; measures superiority over the best parent; commercially more important.
7. Dominance hypothesis: complementation of deleterious recessives; most widely supported. Overdominance hypothesis: heterozygote Aa intrinsically superior to AA and

aa at some loci. Epistasis hypothesis: favourable inter-locus allele interactions more common in hybrids than in inbreds.

8. Inbred lines (A and R) are grown in adjacent rows in an isolation block. In detasselling-based systems, the A-line rows are detasselled (tassels removed before pollen shed) so all seed set on A-line results from cross-pollination by the R-line. Seed harvested from A-line rows is F1 hybrid seed. Farmers must buy new seed each season because F2 segregates, losing heterozygosity and heterosis.
9. White Fulani (local zebu; adapted to heat and disease; low milk yield 400 to 800 litres/lactation) is crossed with Holstein-Friesian (exotic; high milk yield; poor adaptation). F1 cross yields 2,000 to 4,000 litres/lactation, showing heterosis for milk yield, calf survival, and reproductive efficiency.
10. GCA: average performance of a line in crosses with many different testers; reflects additive gene effects; identifies broadly useful parents. SCA: deviation of a specific cross from its GCA prediction; reflects non-additive (dominance and epistatic) effects; identifies pairs that combine especially well for heterosis.

Part 3.2

11. F = probability that the two alleles at any locus are identical by descent. F = 0: random mating; no inbreeding; maximum heterozygosity. F = 1: complete inbreeding; fully homozygous at all loci.
12. Primary cause: increased frequency of homozygous recessive genotypes (aa) that express deleterious phenotypic effects normally masked in heterozygotes. Most affected traits: low-heritability fitness traits (reproductive rate, litter size, neonatal survival, disease resistance).
13. Maize is a naturally cross-pollinating species with high background heterozygosity and many deleterious recessive alleles maintained in a masked state by dominant counterparts; forced selfing rapidly exposes these recessives. Cowpea is naturally self-pollinating; deleterious recessives have been largely purged over evolutionary history of selfing, so further inbreeding has little additional negative effect.
14. Plant breeding: (1) developing homozygous inbred lines as hybrid parents by 6 to 8 generations of selfing; (2) fixing superior allele combinations in stable, true-breeding

variety lines. Animal breeding: linebreeding to concentrate the genetic contribution of an outstanding ancestor while keeping F within acceptable limits (below 5 to 10 percent).

15. $\Delta F \approx 1/(2Ne)$ per generation. With few breeding males (e.g. 2 to 3 bulls; $Ne \approx 8$ to 12), F can accumulate at 4 to 6 percent per generation. Managers must rotate bulls, bring in unrelated sires from other herds or AI centres, and monitor F using pedigree records or SNP-based ROH analysis.

Part 3.3

1. SSI (Brassica): pollen compatibility determined by diploid sporophyte genotype; rejection at stigma surface; SRK-SCR interaction. GSI (Solanaceae): pollen compatibility determined by haploid pollen genotype; tube enters style but arrested by S-RNase.
2. In Brassica: the S-locus encodes two tightly linked genes in the pistil: SRK (S-locus receptor kinase) and SCR (S-locus cysteine-rich protein) in the pollen coat. If pollen and pistil share the same S-allele, SRK recognises SCR, triggers a kinase phosphorylation cascade, activates ARC1 ubiquitin ligase, and suppresses pollen tube germination.
3. Interspecific incompatibility: failure of fertilisation between different species. Pre-fertilisation: different flowering times; pollen too large/small for foreign stigma; pollen-stigma biochemical mismatch; pollen tube arrest in style. Post-fertilisation: endosperm breakdown; hybrid lethality; hybrid sterility from meiotic irregularities.
4. Embryo rescue: excise developing hybrid embryo before abort; culture on artificial medium; used at IITA for Manihot esculenta x wild Manihot crosses. Chromosome doubling with colchicine: doubles chromosome number of sterile F1 hybrid to produce fertile amphidiploid; used in Arachis wide crosses at IAR/ICRISAT.
5. SI parent lines are used as seed parents in hybrid seed production; because pollen from the same SI genotype is rejected, no emasculation is needed; the SI parent sets seed only from cross-pollination by the other parent line; this dramatically reduces hybrid seed production cost in Brussels sprouts, cabbage, and oilseed rape.

Part 3.4

1. GMS: caused by recessive nuclear genes (ms/ms); Mendelian inheritance; maintained by crossing ms/ms x Ms/ms (50 percent sterile progeny). CMS: caused by mitochondrial-

nuclear genome incompatibility; maternally inherited; not Mendelian; all progeny of CMS female are sterile unless a nuclear Rf restorer gene is provided by the pollen parent.

2. A-line (CMS line): cms cytoplasm; ms/ms; male sterile; used as seed parent; crossed with R-line to produce commercial hybrid seed. B-line (maintainer): normal cytoplasm; ms/ms; genetically identical to A-line except for cytoplasm; crossed with A-line to produce more A-line seed each season. R-line (restorer): carries dominant Rf gene; provides pollen to A-line; Rf restores pollen fertility in the F1 hybrid.
3. Sorghum: IAR Zaria uses Milo-CMS cytoplasm for hybrid sorghum production. Pearl millet: IAR Zaria uses Tift 23A CMS source for hybrid pearl millet seed production.
4. Nutritional deficiency (energy deficit causing anoestrus): improve body condition score through balanced feeding before breeding season. Brucellosis (causing endometritis and early embryo death): vaccinate females with S19 or RB51 vaccine; test and cull seropositive animals. Ovarian cysts (failure of ovulation): treat with GnRH or hCG injection; cull non-responding animals. Anatomical defects (freemartinism; congenital uterine abnormalities): check female co-twins with males at birth using vaginal probe test; cull confirmed freemartins.
5. Freemartinism: female calf born co-twin with a male shares a placental anastomosis (blood vessel connection) with the male twin during foetal development. Testosterone and anti-Mullerian hormone from the male foetus cross through this connection and suppress normal development of the Mullerian duct (uterus, oviducts) and ovaries in the female co-twin; approximately 90 percent of such females are infertile.

References and Attributions [Series 3]

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

6. Figure 3.1: Mechanisms of sporophytic (SSI) and gametophytic (GSI) self-incompatibility. Attribution: AI generated. Suggested OER search string: "self-incompatibility sporophytic gametophytic mechanism diagram SSI GSI OER".
7. Box 3.1: Three-line CMS hybrid seed production system with Nigerian sorghum example. Attribution: AI generated. Suggested OER search string: "CMS three-line hybrid seed production A-line B-line R-line cytoplasmic male sterility diagram table OER".

Course code: BIO 402

Course title: Principles of Plant and Animal Breeding

Series 4: Breeding Methods, Pest and Disease Resistance Management

- **Part 4.1: Breeding Methods for Self-Pollinated Crops**
  - Sub Part 4.1.1: Pedigree method
  - Sub Part 4.1.2: Bulk method and single seed descent
  - Sub Part 4.1.3: Backcross breeding
- **Part 4.2: Breeding Methods for Cross-Pollinated Crops**
  - Sub Part 4.2.1: Mass selection and recurrent selection
  - Sub Part 4.2.2: Hybrid breeding
  - Sub Part 4.2.3: Synthetic and composite varieties
- **Part 4.3: Breeding for Pest and Disease Resistance in Plants**
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- **Part 4.4: Breeding for Disease and Parasite Resistance in Animals**
  - Sub Part 4.4.1: Genetic resistance to trypanosomiasis in Nigerian cattle
  - Sub Part 4.4.2: Resistance to Newcastle disease and helminths in Nigerian livestock
  - Sub Part 4.4.3: Strategies for breeding disease-resistant livestock in Nigeria

Introduction

Breeding methods are the systematic procedures by which breeders create, select, and fix desirable genotypes in plant and animal populations. The appropriate method depends critically on the mode of reproduction of the species: self-pollinated crops require approaches that exploit their natural tendency toward homozygosity, while cross-pollinated crops require methods that maintain or harness heterozygosity. Resistance to pests and diseases is among the most important traits in both crop and livestock improvement; it reduces yield losses, lowers production costs, and decreases dependence on chemical inputs.

This Series describes the principal breeding methods used for self-pollinated and cross-pollinated crops in Nigeria, including pedigree selection, bulk method, single seed descent, backcross breeding, mass selection, recurrent selection, hybrid breeding, and synthetic varieties. It then covers the principles of breeding for pest and disease resistance in plants (vertical vs horizontal resistance, sources of resistance, incorporation by backcrossing) and animals (trypanotolerance, Newcastle disease resistance, helminth resistance), with specific reference to Nigerian crops and livestock.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 4.1** describe and compare the pedigree method, bulk method, single seed descent, and backcross method for breeding self-pollinated crops (Linked to Part 4.1),
- **SLO 4.2** describe mass selection, recurrent selection, hybrid breeding, and synthetic variety development for cross-pollinated crops (Linked to Part 4.2),
- **SLO 4.3** distinguish between vertical and horizontal resistance and explain how each is incorporated into improved crop varieties (Linked to Part 4.3),
- **SLO 4.4** describe sources of resistance and the screening methods used in Nigerian crop breeding programmes (Linked to Part 4.3),

- **SLO 4.5** explain the genetic basis of trypanotolerance in Nigerian cattle and describe breeding strategies that exploit it (Linked to Part 4.4), and
- **SLO 4.6** describe breeding approaches for resistance to Newcastle disease and helminths in Nigerian livestock (Linked to Part 4.4).

4.1 Breeding Methods for Self-Pollinated Crops

4.1.1 Pedigree method

The pedigree method is the standard procedure for breeding self-pollinated crops (rice, wheat, cowpea, soybean, groundnut). Two parents with complementary traits are crossed to produce the F1; the F1 is selfed to produce an F2 population showing segregation for all traits. Individual F2 plants are selected based on phenotype and are grown as F3 families (one row per selected F2 plant); individual plants are again selected within the best F3 families to produce F4 families; selection continues family by family through F5 to F7 generations until lines breed true. Throughout the process, the breeder maintains a written pedigree record of the parentage of each selected line; this pedigree allows retrospective analysis of which crosses and selection decisions produced the best lines.

Advantages of the pedigree method: early selection in F2 and F3 allows elimination of inferior genotypes before large amounts of resources are invested; the pedigree record provides information on the genetic background of each line; selection at each generation is based on the performance of individual plants and families in the target environment. Disadvantages: labour-intensive; large numbers of rows must be maintained; field space requirements are high in early generations; genotype x environment interaction may mislead selection in early segregating generations. In Nigeria, the pedigree method is used at IITA for cowpea improvement, at NCRI for upland rice improvement, and at IAR for groundnut breeding. Typically 4 to 6 years are needed from the initial cross to a candidate advanced line.

Fill in the blank: In the pedigree method, the written record of the parentage and selection history of each breeding line from the initial cross through successive selfing generations is

called the _____; it allows the breeder to trace the origin of each superior line and to understand which parental combinations are most productive.

4.1.2 Bulk method and single seed descent

The bulk method avoids individual plant selection in early segregating generations. After the F1 cross, the F2 and subsequent generations (F3 to F5) are grown as bulk populations: all plants are harvested together and a random sample of seed is sown the next season. Natural selection operates on the bulk, favouring better-adapted genotypes; no artificial selection is applied until F5 or F6, when individual plant selection begins. From F6 onward, selected individual plants are grown as families and evaluated as in the pedigree method. The bulk method is simpler and cheaper than pedigree selection (no family records maintained in early generations), but early-generation natural selection may not align with the breeder's target traits.

Single seed descent (SSD) is a modification in which exactly one seed per plant is advanced to the next generation, regardless of performance. This rapidly advances generations toward homozygosity (6 to 7 generations in 3 to 4 years using off-season nurseries or rapid generation advance under controlled environments) without applying selection, preserving maximum genetic diversity from the F2 for selection in later generations. SSD is particularly useful when multiple generations per year can be achieved (off-season nursery in a different agro-ecological zone; greenhouse cycling). IITA uses SSD for cowpea and soybean improvement, achieving 3 to 4 generations per year using off-season nurseries at Kano, Zaria, and Ibadan, reducing the breeding cycle from 8 to 10 years (pedigree) to 4 to 5 years.

Fill in the blank: Single seed descent (SSD) advances generations toward homozygosity rapidly by taking exactly _____ seed from each plant each generation, without applying selection; this preserves maximum F2 diversity for selection at high levels of homozygosity.

4.1.3 Backcross breeding

Backcross breeding is used to transfer a specific desirable gene (most commonly a disease or pest resistance gene) from a donor parent into an otherwise elite, adapted variety (the recurrent parent) without substantially altering the recurrent parent's other agronomic characteristics. The

procedure: the donor parent (carrying the resistance gene) is crossed with the recurrent parent to produce the F1; the F1 is crossed back (backcrossed) to the recurrent parent to produce BC1F1; the backcross is repeated 5 to 6 times (BC5 or BC6), selecting in each generation for the resistance gene and for recurrent parent phenotype; after the final backcross, the selected BC5F1 (or BC6F1) is selfed to fix homozygosity for the resistance allele (R/R or rr) and to stabilise the recurrent parent genome.

After 5 to 6 backcross generations, the backcross-derived line contains approximately 98.4 percent of the recurrent parent genome and only 1.6 percent of the donor parent genome, retaining the resistance gene and eliminating the donor's other (often inferior) agronomic characteristics. Marker-assisted backcrossing (MABC) uses flanking molecular markers to: (1) select for the target gene (foreground selection); (2) select against donor chromatin outside the target region (background selection), accelerating genome recovery in 3 to 4 backcross generations instead of 5 to 6. MABC is used at IITA to introgress cassava mosaic disease (CMD) resistance, cassava brown streak disease (CBSD) resistance, and drought tolerance QTLs into elite West African cassava backgrounds.

Fill in the blank: After 6 backcross generations with the recurrent parent, the backcross-derived line contains approximately _____ percent of the recurrent parent genome; the remaining small fraction contains the target gene transferred from the donor parent.

Pilot questions 4.1

- Outline the steps of the pedigree method from F1 to release of an improved variety.
- Distinguish between the bulk method and single seed descent (SSD) and state one advantage of each.
- Explain why backcross breeding is preferred over pedigree selection when the objective is to add disease resistance to an existing elite variety.
- How does marker-assisted backcrossing (MABC) accelerate the backcross breeding process?
- State two self-pollinated crops bred by the pedigree method in Nigeria and the institutions involved.

4.2 Breeding Methods for Cross-Pollinated Crops

4.2.1 Mass selection and recurrent selection

Mass selection is the simplest breeding method for cross-pollinated crops: superior individual plants are identified based on their phenotype and their seed is bulked together to form the next generation population. Mass selection improves only the seed (female) parent half of the population because pollination is uncontrolled; it is most effective for highly heritable traits (plant height, flowering time, seed colour). It is widely used by Nigerian farmers for on-farm selection of improved open-pollinated maize, sorghum, and pearl millet varieties and contributes to local adaptation of introduced varieties. Several cycles of mass selection can significantly improve a population for moderately heritable traits.

Recurrent selection improves both the male and female parent contribution by controlling pollination within selected individuals. Simple recurrent selection (SRS): select superior plants, intermating them in a crossing block, and evaluate progeny. Half-sib recurrent selection (HS-RS): each selected plant is testcrossed; plants with superior half-sib progeny are identified; their remnant seed is bulked and intermated. Full-sib recurrent selection: both parents of each pair are identified and evaluated through their progeny. Reciprocal recurrent selection (RRS): two populations are improved simultaneously for their combining ability with each other; the basis for developing heterotic groups in maize (Stiff Stalk x non-Stiff Stalk in temperate maize; CIMMYT pool-A x pool-B in tropical maize used at IITA for Nigerian hybrid development). RRS is the most powerful approach for developing heterotic populations for hybrid breeding.

Fill in the blank: _____ recurrent selection simultaneously improves two populations for their combining ability with each other; it is used to develop heterotic groups in maize, where one population serves as the seed parent pool and the other as the pollen parent pool for hybrid variety production.

4.2.2 Hybrid breeding

Hybrid breeding produces F1 hybrid varieties by crossing two distinct, homozygous (inbred) lines or breeds. The steps are: (1) develop inbred lines by 6 to 8 generations of selfing; (2) evaluate lines for GCA and SCA in testcrosses and diallel crosses; (3) identify the best hybrid combinations; (4) produce hybrid seed commercially using male sterility (CMS system), self-incompatibility, or mechanical detasselling. Hybrid varieties require new seed to be purchased each season; they are not farmer-saved. For the breeder, maintaining, refreshing, and commercialising inbred lines is a continuing requirement.

In Nigeria, IITA and NCRI have released open-pollinated varieties (OPVs) and hybrid varieties of maize; hybrids include SAMMAZ 14, 15, and subsequent releases with yields of 5 to 7 t/ha under good management, compared with 1 to 2 t/ha for local varieties. IAR Zaria has released hybrid sorghum using Milo-CMS cytoplasm and hybrid pearl millet using Tift 23A CMS. NCRI Badeggi is developing hybrid rice using the WA-CMS system. The commercial hybrid seed industry in Nigeria is growing, with companies such as Seed Co, DuPont Pioneer (Corteva), Syngenta, and local firms distributing hybrid maize seed. However, smallholder adoption is constrained by seed cost, limited rural seed markets, and the cultural practice of saving seed.

Fill in the blank: SAMMAZ hybrid maize varieties released by IITA and NCRI yield _____ to 7 tonnes per hectare under good management, compared with 1 to 2 t/ha for unimproved local open-pollinated varieties grown by Nigerian smallholders.

4.2.3 Synthetic and composite varieties

A synthetic variety is produced by intermating a defined set of inbred lines or clones in all combinations for one or two generations, then releasing the resulting random-mating population as a variety. Synthetics are intermediate between OPVs and hybrids: they exploit some of the combining ability of their parent lines but are not as uniform as hybrids; they can be maintained by farmers through open pollination without purchasing new seed each season. They are suited to resource-poor smallholder environments where hybrid seed supply chains are unreliable. Synthetic varieties of maize, sorghum, and pearl millet have been developed at IITA and IAR for Nigerian smallholders.

A composite variety is produced by intercrossing a broader set of genotypes (often including landraces, improved varieties, and exotic material) in all combinations, then releasing the population after one or two generations of random mating. Composites maintain higher genetic diversity than synthetics and can adapt over time through farmer selection. The IITA Tropical Maize Composite (TZMB and TZESR composites) is an example; it provides a broadly adapted, disease-tolerant population from which farmers can select preferred plant types. Both synthetics and composites represent practical solutions for situations where the full infrastructure for hybrid seed production and distribution is not yet available.

Fill in the blank: A _____ variety is produced by intercrossing a defined set of improved inbred lines in all combinations and releasing the random-mating population; it is intermediate in performance between an open-pollinated variety and a hybrid, and can be maintained by farmers through open pollination.

Pilot questions 4.2

- Distinguish between mass selection and half-sib recurrent selection for cross-pollinated crops.
- Explain why reciprocal recurrent selection (RRS) is used in developing heterotic groups for hybrid maize breeding.
- Describe the steps of hybrid variety development from inbred line development to commercial hybrid seed production.
- Distinguish between a synthetic and a composite variety and state one advantage of each over a hybrid variety for Nigerian smallholders.
- Name two hybrid crop varieties released in Nigeria and state the institution and the crop for each.

4.3 Breeding for Pest and Disease Resistance in Plants

4.3.1 Nature of resistance: vertical and horizontal resistance

Plant resistance to pests and diseases is the ability of a plant to reduce the growth, development, or reproduction of a pathogen or pest relative to a susceptible host. Resistance is classified as vertical (race-specific) or horizontal (race-non-specific). Vertical resistance (VR) is controlled by one or a few major genes (R-genes) and is effective only against specific races or biotypes of the pathogen; it is highly effective (immunity or near-immunity in resistant plants) but not durable because new virulent races of the pathogen can evolve and overcome it. The gene-for-gene relationship (Flor, 1956) describes the interaction: resistance in the host (R-gene) is matched by avirulence (Avr-gene) in the pathogen; virulence evolves when the pathogen loses or mutates its Avr-gene.

Horizontal resistance (HR) is controlled by many genes each of small effect (polygenic); it is effective against all or most races of a pathogen but only partially reduces infection rather than preventing it; it is more durable because new pathogen races rarely overcome all HR loci simultaneously. HR is sometimes called field resistance or partial resistance. In Nigeria, the most practically important examples are: vertical resistance to cassava mosaic disease (CMD2 gene; highly effective against most CMV biotypes in West Africa; used at IITA in cassava improvement since the 1990s); horizontal resistance to grey leaf spot and northern corn leaf blight in IITA maize varieties; and polygenic resistance to late leaf spot and rust in IAR groundnut varieties. Gene pyramiding (stacking multiple R-genes and HR QTLs in the same variety) is used to broaden and prolong the durability of resistance.

Fill in the blank: _____ resistance is controlled by one or a few major R-genes; it provides immunity or near-immunity against specific pathogen races but is not durable because new virulent races can evolve; the gene-for-gene relationship describes its molecular basis.

4.3.2 Sources of resistance and screening methods

Sources of resistance used in Nigerian crop breeding include: landraces and traditional cultivars (many Nigerian farmers' varieties carry partial resistance to locally prevalent diseases accumulated over generations of local selection; IAR maintains extensive groundnut landrace collections with late leaf spot and rosette virus resistance); wild relatives of crops (wild Arachis species carry strong resistance to late leaf spot, early leaf spot, and peanut rosette; wild Manihot

species carry resistance to CMD and CBSD; accessible through wide hybridisation and embryo rescue); introduced germplasm from international centres (CIMMYT streak-resistant maize lines; IRRI blast-resistant rice varieties; ICRISAT Striga-resistant sorghum and pearl millet lines); and induced mutants (gamma-ray or EMS mutants with altered susceptibility).

Screening methods for resistance must expose plants to the target pathogen or pest under controlled, repeatable conditions. Artificial inoculation methods include: spraying spore suspensions of fungal pathogens onto leaves at the appropriate growth stage (late leaf spot in groundnut; grey leaf spot in maize); injecting bacterial suspensions into stems or leaf petioles (cassava bacterial blight); viruliferous insect inoculation using whiteflies carrying CMV for CMD screening; and Striga seed incorporation into the soil for Striga-resistance screening in sorghum and cowpea at IAR and IITA. Scoring scales (1 to 9; 0 to 5) measure disease severity; resistant plants score 1 to 3 and susceptible plants score 7 to 9. Multi-season screening in disease hotspot locations ensures robust resistance evaluation.

Fill in the blank: In cassava mosaic disease (CMD) resistance screening at IITA, plants are inoculated using _____ insects (whiteflies, Bemisia tabaci) that carry the cassava mosaic begomovirus; resistant plants show no or minimal leaf mosaic symptoms while susceptible checks show severe mosaic and stunting.

4.3.3 Incorporating resistance into improved varieties

Once sources of resistance are identified, resistance alleles are incorporated into elite genetic backgrounds using three main approaches. Backcross breeding (described in Part 4.1.3) is the most common method for transferring a single major resistance gene from a donor into an elite variety without altering other traits; it is used at IITA to introgress CMD2 resistance into high-yielding cassava backgrounds, and at IAR to transfer rosette virus resistance into adapted groundnut varieties. Pedigree selection from crosses between resistant and high-yielding parents is used when multiple resistance genes or resistance combined with yield improvement are needed simultaneously; the breeder selects resistant, high-yielding plants in F3 to F6 families.

Pyramiding (gene stacking) combines two or more independent resistance genes into a single variety to broaden the spectrum and increase durability of resistance. For example, pyramiding

CMD2 and CBSD resistance in cassava requires crossing donor lines carrying each gene separately, then selecting in segregating populations for plants homozygous for both resistance alleles; molecular markers (MAS) greatly simplify selection for two or more resistance genes simultaneously without requiring disease screening for each gene individually. In rice blast resistance improvement at NCRI Badeggi, blast R-genes Pi9, Pita, and Pi33 are being pyramided into FARO 44 using MAS. Marker-assisted selection reduces the number of generations and field seasons required to confirm resistance genotype, accelerating the variety development pipeline.

Fill in the blank: Gene _____ combines two or more independent resistance genes into a single variety; in cassava improvement at IITA, CMD2 (cassava mosaic disease resistance) and CBSD resistance genes are stacked using molecular markers to select plants homozygous for both resistance alleles simultaneously.

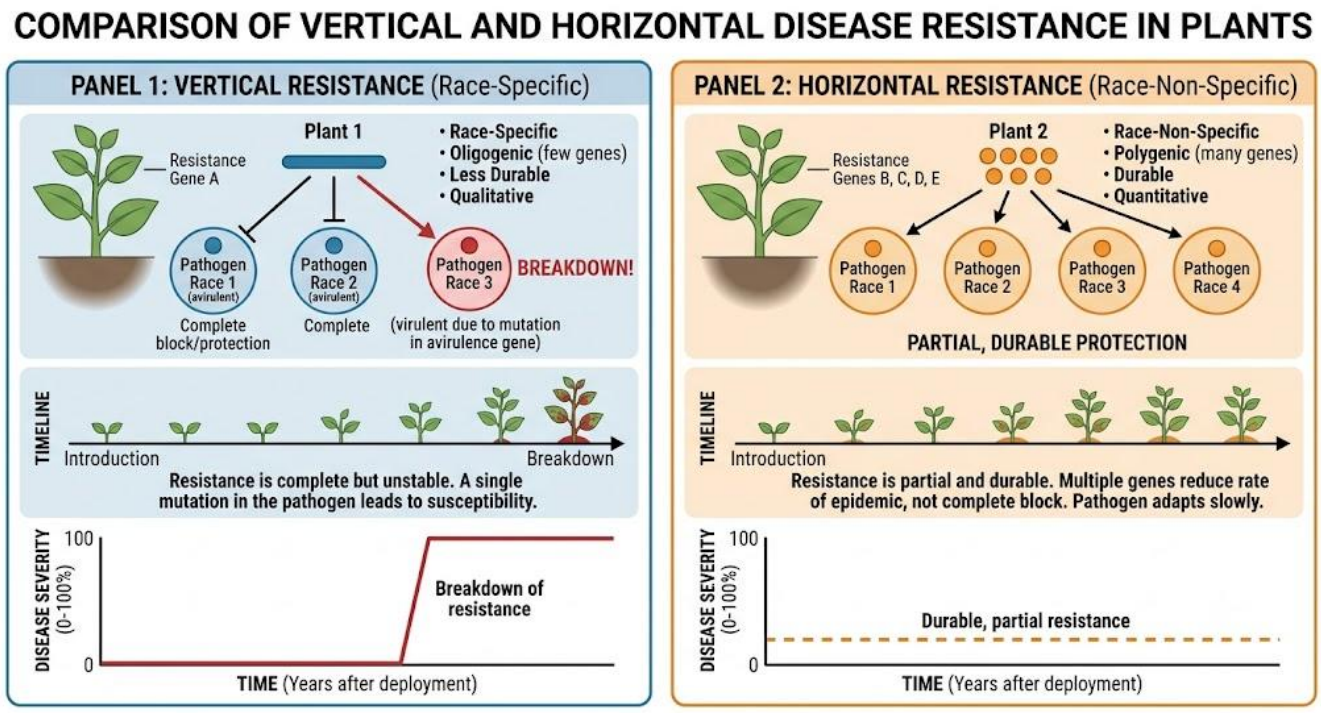

Figure 4.1: Comparison of vertical (race-specific) and horizontal (polygenic) resistance to crop pathogens

Pilot questions 4.3

1. Distinguish between vertical and horizontal resistance and state one advantage and one disadvantage of each.
2. State four sources of resistance exploited in Nigerian crop breeding and give one example for each source.
3. Describe the screening method used to evaluate cassava mosaic disease (CMD) resistance at IITA.
4. Explain how backcross breeding is used to incorporate disease resistance into an elite cassava variety.
5. What is gene pyramiding and why is it used in resistance breeding?

4.4 Breeding for Disease and Parasite Resistance in Animals

4.4.1 Genetic resistance to trypanosomiasis in Nigerian cattle

African animal trypanosomiasis (AAT; nagana) is caused by Trypanosoma brucei brucei, T. congolense, and T. vivax, transmitted by tsetse flies (Glossina species). It is the most economically important disease of Nigerian cattle, rendering approximately 10 million km2 of sub-Saharan Africa (the tsetse belt) uninhabitable by susceptible exotic cattle breeds. Trypanotolerance is the ability to remain productive (maintain weight, reproduce, and sustain acceptable haematocrit) despite Trypanosoma infection, without drug treatment. It is not immunity (tolerant animals are still infected) but the capacity to control anaemia and maintain production under infection.

In Nigeria, the trypanotolerant breeds are the N'Dama (Bos taurus; longhorn; adapted to the Guinea forest and derived savanna zones of south-west and central Nigeria) and the West African Dwarf (WAD) shorthorn cattle (Bos taurus; small frame; forest zone). Both are of taurine (Bos taurus) rather than zebu (Bos indicus) origin; taurine cattle are significantly more trypanotolerant than zebu. The genetic basis of trypanotolerance is polygenic: QTL studies by the International Livestock Research Institute (ILRI) and collaborators have identified several

genomic regions on chromosomes 2, 4, 5, 7, and 23 that contribute to haematocrit maintenance and control of peak parasitaemia. The heritability of trypanotolerance traits (haematocrit, liveweight under challenge) is 0.10 to 0.25, meaning that selection response is possible but slow.

Fill in the blank: The trypanotolerant cattle breed found in the Guinea forest and derived savanna zones of south-western Nigeria, characterised by its long horns and Bos taurus ancestry, is the _____; it can maintain productive capacity under Trypanosoma infection without drug treatment.

4.4.2 Resistance to Newcastle disease and helminths in Nigerian livestock

Newcastle disease (ND) is caused by avian paramyxovirus-1 (APMV-1) and is the most economically important disease of Nigerian village poultry, causing 70 to 80 percent mortality in unvaccinated flocks during outbreaks. Genetic resistance to ND varies between poultry populations: local Nigerian ecotype chickens (Fulani, Yoruba, and Igbo ecotypes) show significantly higher survival rates during ND outbreaks than imported exotic breeds; survival rates of 40 to 60 percent in local ecotypes compared with near-zero survival in unvaccinated exotic lines have been reported. Genetic resistance is polygenic; it involves the MHC (major histocompatibility complex) region on chromosome 16 in chickens, which influences immune response to viral pathogens. FUNAAB and ABU have conducted selection programmes to identify and multiply ND-tolerant local ecotype lines for distribution to smallholder poultry farmers.

Helminth (gastrointestinal nematode) resistance is important in sheep, goats, and cattle across Nigeria. Resistant animals show reduced worm burdens (faecal egg counts, FEC), less anaemia (FAMACHA score), and better growth rates under helminth challenge compared with susceptible animals. In West African Dwarf (WAD) goats and Djallonke sheep, genetic variation in helminth resistance is well documented; heritability of FEC is 0.15 to 0.35, indicating a moderate response to selection. The FECPAK faecal egg count method is used to phenotype resistance: animals with consistently low FEC under natural challenge are identified and used as parents in the next generation. FUNAAB and the International Trypanotolerance Centre (ITC)

Banjul have conducted selection for helminth resistance in WAD goats and Djallonke sheep in West Africa.

Fill in the blank: In helminth resistance breeding for Nigerian sheep and goats, animals are ranked by their _____ egg count (FEC) measured from faecal samples; animals with consistently low FEC under natural challenge conditions are identified as genetically resistant and selected as breeding parents.

4.4.3 Strategies for breeding disease-resistant livestock in Nigeria

Three complementary strategies are used to improve disease resistance in Nigerian livestock. Selection within locally adapted breeds: identify and multiply genetically resistant individuals within N'Dama, WAD goat, Djallonke sheep, and local poultry ecotype populations; use estimated breeding values (EBVs) based on phenotypic data (haematocrit, FEC, ND survival) and pedigree information to rank animals; mate the highest-EBV individuals; monitor response over 3 to 5 generations. This approach is slowest per generation but maintains the local adaptation package alongside resistance. Crossbreeding: crossing trypanotolerant N'Dama with improved zebu (White Fulani) or taurine breeds produces F1 crosses that combine N'Dama trypanotolerance with improved meat or milk production; the cross requires careful management of the tsetse-tolerance level in the resulting animals.

Genomic tools: ILRI has developed a low-density SNP chip (10,000 SNPs) for West African cattle breeds including N'Dama and WAD; genomic selection using this chip can predict GEBVs for trypanotolerance traits at birth, allowing selection of superior sires at a young age before challenge testing. MAS for known trypanotolerance QTLs (on chromosomes 2, 4, 5) can identify carriers of favourable alleles for introgression into White Fulani or Bunaji zebu backgrounds. Integration of disease management (trypanosome drug treatment as rescue, not as routine prophylaxis; selective treatment of only FAMACHA-score-positive animals for helminths) with genetic improvement of resistance reduces selection pressure for drug resistance in parasites and maximises the benefit of the host genetic resistance programme.

Fill in the blank: Genomic selection for trypanotolerance using a low-density _____ chip developed by ILRI allows breeders to predict breeding values for haematocrit maintenance and

parasite control in West African cattle at birth, without waiting for expensive tsetse-challenge tests.

Strategy	Trait Targeted	Breed/Species	Institution	Genetic Tool Used
Within-breed selection for trypanotolerance	Resistance to trypanosome infection (trypanosomiasis)	N'Dama cattle, Muturu cattle	National Animal Production Research Institute (NAPRI), Zaria	Phenotypic selection, pedigree analysis
Newcastle disease resistance	Resistance to viral Newcastle disease	Indigenous Nigerian chickens	Federal University of Agriculture, Abeokuta (FUNAAB)	Marker-assisted selection (MAS) using immune response genes
Helminth resistance	Resistance to gastrointestinal nematodes	West African Dwarf goats, sheep	University of Ibadan, Faculty of Veterinary Medicine	Quantitative trait loci (QTL) mapping, fecal egg count selection
Crossbreeding	Combining disease resistance with productivity traits	Zebu × Muturu cattle, exotic × local poultry	NAPRI Zaria, Obafemi Awolowo University	Controlled crossbreeding, performance testing
Genomic selection	Genome-wide prediction of disease resistance traits	Cattle, poultry, small ruminants	International Institute of Tropical Agriculture (IITA),	SNP genotyping, genomic prediction models

			NACGRAB Ibadan	

Box 4.1: Strategies for breeding disease-resistant livestock in Nigeria

Pilot questions 4.4

1. Define trypanotolerance and explain why it differs from immunity to trypanosomiasis.
2. Name two trypanotolerant cattle breeds in Nigeria and state the agro-ecological zone where each is kept.
3. Explain the genetic basis of trypanotolerance and state its heritability range.
4. Describe how Nigerian local ecotype poultry show genetic resistance to Newcastle disease compared with exotic breeds.
5. Explain how FECPAK faecal egg counting is used to screen for helminth resistance in WAD goats.

Series Summary

Breeding methods for self-pollinated crops include pedigree selection, bulk breeding, single seed descent, and backcross breeding. Pedigree selection involves choosing individual plants from F2 to F7 while maintaining ancestry records and is used for crops such as cowpea, rice, and groundnut. The bulk method allows generations F2 to F5 to grow under natural selection before individual plants are selected from F6. Single seed descent advances one seed from each plant per generation, enabling rapid homozygosity, especially with off-season nurseries. Backcross breeding transfers a desired gene from a donor into an elite recurrent parent, while marker-assisted backcrossing speeds up recovery of the recurrent-parent genome. In cross-pollinated crops, mass selection improves populations through superior phenotypes, recurrent selection improves parental populations and develops heterotic groups, while hybrid breeding crosses selected inbred lines to produce high-performing varieties such as SAMMAZ maize. Synthetic and composite varieties are developed from selected parents and can be maintained by farmers.

Plant disease resistance may be vertical or horizontal. Vertical resistance is controlled by major genes, is race-specific and highly effective, but is often less durable, while horizontal resistance is polygenic, partial, and generally more durable. Resistance genes may come from landraces, wild relatives, or international germplasm and are identified through methods such as artificial inoculation, spore spraying, whitefly transmission for cassava mosaic disease, and Striga seed incorporation into soil. These genes may be introduced through backcrossing, pedigree selection, or marker-assisted gene pyramiding. In animals, disease-resistance breeding includes trypanotolerance in N'Dama and West African Dwarf cattle, Newcastle disease resistance in local poultry, and helminth resistance in West African Dwarf goats and Djallonke sheep. Trypanotolerance has a heritability of $\mathbf{h^2 = 0.10–0.25}$, while faecal egg count resistance has a heritability of $\mathbf{h^2 = 0.15–0.35}$. Major improvement strategies include within-breed selection, crossbreeding, and genomic selection using tools such as the ILRI 10K SNP chip.

Glossary of Terms

1. **Backcross breeding:** a method of transferring a specific gene from a donor parent into an elite recurrent parent through repeated backcrossing; the recurrent parent genome is recovered at approximately 98.4 percent after 6 backcross generations.
2. **Bulk method:** a breeding method for self-pollinated crops in which segregating populations (F2 to F5) are harvested in bulk without selection; individual plant selection begins at F5 or F6 when homozygosity is high.
3. **Composite variety:** a population variety produced by intercrossing a broad set of genotypes in all combinations; maintains high genetic diversity; can adapt over time through farmer selection; example: IITA Tropical Maize Composite.
4. **FECPAK:** a portable laboratory system used to count helminth eggs in animal faeces; animals with low faecal egg counts (FEC) under natural challenge are classified as genetically resistant and selected as breeding parents.
5. **Gene pyramiding:** the stacking of two or more independent resistance genes into a single variety to broaden resistance spectrum and increase durability; facilitated by marker-assisted selection.

6. **Half-sib recurrent selection (HS-RS):** a recurrent selection method in which each selected plant is testcrossed; plants with superior half-sib progeny are identified; their remnant seed is intermated to form the next cycle.
7. **Horizontal resistance (HR):** polygenic, race-non-specific resistance controlled by many genes of small effect; partial but durable because new pathogen races rarely overcome all resistance loci simultaneously.
8. **Hybrid variety:** an F1 variety produced by crossing two homozygous inbred lines; exploits heterosis; uniform and high-yielding; requires new seed purchase each season.
9. **Marker-assisted backcrossing (MABC):** backcross breeding in which molecular markers are used for foreground selection (target gene) and background selection (recurrent parent genome recovery); reduces backcross generations needed from 6 to 3 to 4.
10. **Pedigree method:** a breeding method for self-pollinated crops in which individual plant selection begins in F2 and continues through successive selfing generations with a written record of parentage maintained for each selected line.
11. **Reciprocal recurrent selection (RRS):** a recurrent selection method that simultaneously improves two populations for their combining ability with each other; used to develop heterotic groups in maize for hybrid breeding.
12. **Single seed descent (SSD):** a method in which exactly one seed per plant is advanced each generation without selection; rapidly achieves homozygosity (6 to 7 generations in 3 to 4 years); used for cowpea and soybean at IITA.
13. **Synthetic variety:** a variety produced by intermating a defined set of inbred lines in all combinations and releasing the random-mating population; intermediate in performance between OPV and hybrid; can be maintained by farmers.
14. **Trypanotolerance:** the ability of certain cattle breeds (N'Dama, West African Dwarf) to remain productive under Trypanosoma infection without drug treatment; polygenic trait; h2 = 0.10 to 0.25.
15. **Vertical resistance (VR):** major-gene, race-specific resistance controlled by one or a few R-genes; highly effective against specific pathogen races but not durable because new virulent races can evolve to overcome it.

Concept Check Questions [Series 4]

Objective Questions

1. The breeding method that transfers a specific gene from a donor parent into an elite variety through repeated backcrossing is called _____ breeding. (Linked to SLO 4.1)
2. Single seed descent achieves near-complete homozygosity after 6 to 7 generations by taking exactly _____ seed per plant each generation without applying selection. (Linked to SLO 4.1)
3. _____ recurrent selection simultaneously improves two populations for their combining ability with each other and is used to develop heterotic groups for maize hybrid breeding. (Linked to SLO 4.2)
4. _____ resistance is race-non-specific, controlled by many genes of small effect, partial but durable; it is also called field or partial resistance. (Linked to SLO 4.3)
5. The trypanotolerant cattle breed found in south-western Nigeria, characterised by its long horns and Bos taurus ancestry, is the _____. (Linked to SLO 4.5)

Short-Answer Questions

- Compare the pedigree method and single seed descent for breeding self-pollinated crops. (Linked to SLO 4.1)
- Distinguish between mass selection and reciprocal recurrent selection and state when each is used. (Linked to SLO 4.2)
- Distinguish between vertical and horizontal resistance and give one Nigerian crop example of each. (Linked to SLO 4.3)
- Describe how gene pyramiding is used to improve resistance durability in cassava breeding. (Linked to SLO 4.4)
- Explain the breeding strategy used to improve trypanotolerance in N'Dama cattle in Nigeria. (Linked to SLO 4.5)

Long-Answer Questions

1. Describe the pedigree method, bulk method, SSD, and backcross breeding for self-pollinated crops. State the Nigerian institution and crop for each method. (Linked to SLO 4.1)
2. Describe the breeding methods for cross-pollinated crops (mass selection, recurrent selection, hybrid breeding, synthetic varieties). Explain vertical and horizontal resistance and how resistance is incorporated into improved varieties. (Linked to SLOs 4.2, 4.3, 4.4)
3. Describe the genetic basis and breeding strategies for trypanotolerance, Newcastle disease resistance, and helminth resistance in Nigerian livestock. (Linked to SLOs 4.5, 4.6)

Answers to Concept Check Questions [Series 4]

Objective Questions

6. Backcross.
7. One.
8. Reciprocal.
9. Horizontal.
10. N'Dama.

Short-Answer Questions

11. Pedigree method: individual plant selection from F2 onwards; pedigree records maintained; labour-intensive; 4 to 6 years to advanced line. SSD: one seed per plant per generation; no selection until homozygosity reached; faster (3 to 4 years using off-season nurseries); maximum F2 diversity preserved for later selection.
12. Mass selection: individual plants selected by phenotype; pollen uncontrolled; only female half improved; effective for highly heritable traits; simple; used in farmer-level variety improvement. RRS: two populations improved simultaneously for combining ability; pollination controlled; both parents improved; develops heterotic groups; used in formal hybrid maize breeding.
13. Vertical resistance: race-specific; one or few major R-genes; complete protection against specific races; not durable; example: CMD2 gene for cassava mosaic disease resistance at

IITA. Horizontal resistance: race-non-specific; polygenic; partial but durable; example: polygenic resistance to late leaf spot in IAR groundnut varieties.

14. Pyramiding stacks CMD2 (cassava mosaic disease resistance) and CBSD resistance genes from separate donor lines into a single elite cassava background; plants homozygous for both genes are identified using flanking molecular markers, avoiding the need to disease-screen for each gene separately; the pyramid provides broader spectrum and more durable resistance than either gene alone.
15. Select highest-EBV N'Dama bulls based on haematocrit maintenance and liveweight under trypanosome challenge; mate to N'Dama cows; evaluate progeny under natural tsetse challenge; repeat over 3 to 5 generations. Genomic tools (ILRI 10K SNP chip) allow GEBV prediction at birth, shortening generation interval.

Long-Answer Questions

1. Pedigree method: cross parents; select superior F2 plants; grow F3 families; continue selection through F5 to F7; release promising lines; used at IITA (cowpea), NCRI (rice), IAR (groundnut). Bulk method: harvest F2 to F5 as bulk without selection; individual selection from F6; simpler but early natural selection may not match breeder goals. SSD: one seed per plant each generation; 3 to 4 years to homozygosity using off-season nurseries; used at IITA (cowpea, soybean). Backcross breeding: donor x recurrent parent; 5 to 6 backcrosses; retains 98.4 percent recurrent parent genome; MABC cuts this to 3 to 4 generations; used at IITA for CMD2 and CBSD introgression into cassava.
2. Mass selection: superior phenotypes selected; pollen uncontrolled; simple; used by Nigerian farmers for maize and sorghum. Recurrent selection: HS-RS (half-sib families evaluated); FS-RS (full-sib families); RRS (two heterotic populations improved simultaneously for combining ability; basis of hybrid maize breeding). Hybrid breeding: develop inbred lines (6 to 8 selfing generations); assess GCA/SCA; produce F1 hybrid by crossing A-line x R-line using CMS or detasselling; SAMMAZ maize (IITA/NCRI); sorghum hybrids (IAR). Synthetic variety: intermating of defined inbred lines; farmer-maintainable; IITA tropical maize composites. Vertical resistance: race-specific; major R-gene; effective but not durable (gene-for-gene; new virulent races break it); CMD2 in cassava. Horizontal resistance: polygenic; partial; durable; grey leaf spot resistance in

maize. Sources of resistance: landraces (IAR groundnut), wild relatives (wild Manihot, wild Arachis), CIMMYT/IRRI germplasm. Screening: spore spray (groundnut late leaf spot); whitefly inoculation (CMD); Striga soil incorporation (cowpea, sorghum). Incorporation: backcrossing (CMD2 into cassava); gene pyramiding + MAS (blast R-genes in rice at NCRI).

3. Trypanotolerance: not immunity; capacity to maintain haematocrit and production under Trypanosoma infection. N'Dama (Bos taurus; south-west Nigeria) and WAD shorthorn tolerant; zebu breeds susceptible. Polygenic (QTLs on chromosomes 2, 4, 5, 7, 23); h2 = 0.10 to 0.25. Breeding strategy: within-breed selection using EBVs from haematocrit and liveweight under challenge; ILRI 10K SNP chip for genomic selection; crossbreeding N'Dama x White Fulani to combine trypanotolerance with productivity. Newcastle disease: APMV-1; 70 to 80 percent mortality in unvaccinated flocks; local ecotype chickens (Fulani, Yoruba, Igbo) show 40 to 60 percent survival vs near-zero in exotics; polygenic (MHC chromosome 16); selection programmes at FUNAAB and ABU. Helminth resistance: FEC heritability 0.15 to 0.35 in WAD goats and Djallonke sheep; FECPAK screening; select low-FEC animals as parents; selective anthelmintic treatment based on FAMACHA scores conserves treatment efficacy; FUNAAB and ITC Banjul lead selection work.

Answers to Pilot Questions [Series 4]

Part 4.1

6. F1 from two-parent cross; F2 grown; superior plants selected; selected F2 plants grown as F3 rows; best plants selected within best rows; continue through F4 to F6 until lines breed true; submit stable lines to multi-location trials; release through NVRC.
7. Bulk method: F2 to F5 harvested as bulk without selection; individual selection begins at F6; cheaper and simpler. SSD: one seed per plant per generation; reaches homozygosity in 3 to 4 years; preserves maximum F2 diversity for late-generation selection.

8. Backcross breeding adds only the target resistance gene while recovering the elite variety's entire agronomic package; pedigree selection from a resistant x elite cross risks losing valuable agronomic traits in early-generation selection because the donor parent often has inferior adaptation.
9. MABC uses flanking markers for foreground selection (confirms target gene present) and background markers for selection against donor chromatin elsewhere in the genome; recurrent parent genome is recovered in 3 to 4 backcross generations instead of 5 to 6, saving 2 to 3 years.
10. Cowpea: IITA Ibadan (pedigree method; IT97K-499-35 and related lines). Rice: NCRI Badeggi (pedigree method; FARO series varieties).

Part 4.2

11. Mass selection: individual plants selected by own phenotype; pollination uncontrolled; only female half of population improved per cycle. HS-RS: plants testcrossed; half-sib progeny evaluated; best plants' remnant seed intermated; both parental halves assessed; more effective for low-heritability traits.
12. RRS simultaneously improves two populations (e.g. Pool A and Pool B) for combining ability with each other; this builds genetic divergence between the two pools, maximising heterosis in A x B hybrids; it is the most effective strategy because both the seed-parent pool and the pollen-parent pool are improved for their mutual combining performance.
13. Develop inbred lines by 6 to 8 generations of selfing; evaluate in testcrosses for GCA; identify high-SCA pairs in diallel crosses; produce hybrid seed by crossing A-line (CMS; seed parent) x R-line (pollen parent) in isolation block; package and distribute certified hybrid seed through NASC-accredited producers.
14. Synthetic: defined inbred lines intermated; more uniform; slightly higher yield than composite. Advantage over hybrid: farmers can save and replant seed across seasons without yield penalty from F2 segregation. Composite: broader genetic base; more diversity; adapts to local conditions through farmer selection over years.
15. SAMMAZ 14 (hybrid maize; IITA/NCRI; 5 to 7 t/ha). IAR Hybrid Sorghum SAMSORG 17 (IAR Zaria; Milo-CMS system).

Part 4.3

1. Vertical resistance: race-specific; major R-gene; complete protection; not durable (new races overcome it). Horizontal resistance: race-non-specific; polygenic; partial; durable. Advantage of VR: provides strong protection when deployed. Advantage of HR: long-lasting across pathogen race shifts.
2. Landraces: IAR groundnut varieties carrying partial late leaf spot resistance accumulated by farmer selection. Wild relatives: wild Arachis species with strong late leaf spot resistance used at IAR/ICRISAT wide crosses. International germplasm: CIMMYT streak-resistant maize lines introduced at IITA. Induced mutants: EMS-mutant sorghum lines with altered disease response at IAR Zaria.
3. Viruliferous Bemisia tabaci whiteflies carrying cassava mosaic begomovirus are caged over test plants for 48 to 72 hours; plants are scored 6 to 8 weeks post-inoculation on a 1 (immune) to 5 (severe mosaic) scale; resistant plants score 1 to 2 and are advanced; susceptible checks score 4 to 5.
4. Select CMD-resistant donor (e.g. TMS 30572 carrying CMD2); cross with elite susceptible recurrent parent; backcross F1 to recurrent parent 4 to 5 times, selecting for CMD resistance (by inoculation or CMD2 flanking markers) and for recurrent parent agronomic type at each generation; self BC4 or BC5 to fix resistance; evaluate fixed lines in multi-location trials.
5. Gene pyramiding combines two or more resistance genes in one variety; used because a single major gene can be overcome by new pathogen races (durability problem); pyramiding CMD2 + CBSD resistance in cassava means the pathogen must simultaneously overcome two independent resistance mechanisms, greatly reducing the probability of complete resistance breakdown.

Part 4.4

1. Trypanotolerance is the capacity to remain productive (maintain body weight, haematocrit, and reproduction) under Trypanosoma infection without drug treatment. It differs from immunity because tolerant animals are still infected and carry parasites; they simply control anaemia and maintain production rather than clearing the infection.

2. N'Dama (Bos taurus; longhorn; Guinea forest zone and derived savanna of south-west and central Nigeria). West African Dwarf (WAD) shorthorn (Bos taurus; small frame; humid forest zone of south Nigeria and Benin).
3. Polygenic; QTLs on chromosomes 2, 4, 5, 7, and 23 contribute to haematocrit maintenance and parasitaemia control. Heritability of trypanotolerance traits (haematocrit, liveweight under challenge): 0.10 to 0.25; moderate selection response expected but slow per generation.
4. Local ecotype chickens (Fulani, Yoruba, Igbo) survive ND outbreaks at 40 to 60 percent survival rate vs near-zero in unvaccinated exotic lines; the resistance is polygenic; the MHC (major histocompatibility complex) region on chromosome 16 is a key contributor to immune response variation. Selection at FUNAAB and ABU identifies high-survival families for breeding.
5. Faecal samples collected from each animal; eggs counted using a modified McMaster technique with the FECPAK device; animals ranked by FEC; animals with consistently low FEC under natural pasture challenge are designated resistant; their FEC EBVs are estimated from repeated records and used to select breeding parents for the next generation.

References and Attributions [Series 4]

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Figures, Plates, Tables, and Boxes

6. Figure 4.1: Comparison of vertical and horizontal resistance. Attribution: AI generated. Suggested OER search string: “vertical horizontal resistance plant disease race-specific polygenic durability comparison diagram OER”.
7. Box 4.1: Strategies for breeding disease-resistant livestock in Nigeria. Attribution: AI generated. Suggested OER search string: “livestock disease resistance breeding trypanotolerance Newcastle helminth selection genomic Nigeria table OER”.

Course code: BIO 402

Course title: Principles of Plant and Animal Breeding

Series 5: Practical Breeding Practices, Desired Traits, and Farm Record Keeping

- **Part 5.1: Desired Traits in Crop Improvement**
  - Sub Part 5.1.1: Yield and yield components in major Nigerian crops
  - Sub Part 5.1.2: Quality traits in Nigerian crops
  - Sub Part 5.1.3: Adaptation traits: drought, heat, and soil stress tolerance
- **Part 5.2: Desired Traits in Animal Improvement**
  - Sub Part 5.2.1: Productivity traits in Nigerian livestock
  - Sub Part 5.2.2: Adaptation and fitness traits in Nigerian livestock
  - Sub Part 5.2.3: Carcass and product quality traits
- **Part 5.3: Practical Breeding Operations**
  - Sub Part 5.3.1: Crossing techniques in plants
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Introduction

Successful breeding programmes require a clear definition of the traits to be improved before any crosses are made or animals are selected. Desired traits in crops include yield components, nutritional quality, processing characteristics, and adaptation to abiotic stresses such as drought and soil acidity. In animals, desired traits span productivity (milk, meat, eggs, fibre), adaptation to the local environment, reproductive efficiency, and product quality. Without explicit trait definitions and measurable selection criteria, breeding efforts lack direction and genetic progress is slow or inconsistent.

Practical breeding operations, from emasculation and crossing in plants to controlled mating and reproductive technologies in animals, translate genetic knowledge into improved varieties and breeds. Underpinning all these activities is accurate and systematic record keeping: without reliable pedigree, performance, and environmental data, it is impossible to calculate breeding values, track genetic progress, or design future crosses. This Series covers desired traits for Nigerian crops and livestock, the practical techniques of crossing and controlled mating, and the record-keeping systems needed to run effective breeding programmes.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 5.1** identify and describe the principal yield, quality, and adaptation traits targeted in Nigerian crop improvement programmes (Linked to Part 5.1),
- **SLO 5.2** identify and describe the principal productivity, adaptation, and product quality traits targeted in Nigerian animal breeding programmes (Linked to Part 5.2),
- **SLO 5.3** describe the practical crossing techniques used in plant breeding and the controlled mating and reproductive technologies used in animal breeding (Linked to Part 5.3),
- **SLO 5.4** explain the importance of progeny evaluation and multi-environment testing in variety and breed development (Linked to Part 5.3),

- **SLO 5.5** explain the importance of farm record keeping in breeding programmes and describe the types of records required (Linked to Part 5.4), and
- **SLO 5.6** describe standard recording systems used in Nigerian plant and animal breeding programmes. (Linked to Part 5.4).

5.1 Desired Traits in Crop Improvement

5.1.1 Yield and yield components in major Nigerian crops

Grain or root yield is the primary target trait in most Nigerian crop improvement programmes. However, yield is a complex trait that is the product of several component traits, each of which has higher heritability than yield itself and is therefore more amenable to direct selection. Yield components of cereals include: number of panicles or cobs per unit area; number of grains per panicle or cob; and individual grain weight. A breeder who selects for grain number per panicle and grain weight simultaneously will generally achieve greater yield progress than selecting for yield directly. In rice, yield components include panicle number per m2, spikelet number per panicle, spikelet filling percentage, and thousand-grain weight; NCRI Badeggi targets a harvest index above 0.50 in improved upland rice varieties.

In cassava, key yield components are number of storage roots per plant, average root diameter and length, root fresh weight per plant, and dry matter content (percentage starch). IITA's cassava improvement programme targets fresh root yields of 25 to 40 t/ha with dry matter content above 30 percent and harvest index above 0.65. In cowpea, yield components are number of pods per plant, seeds per pod, and seed weight; IITA IT97K-499-35 achieves 1.5 to 2.0 t/ha under good management versus 0.3 to 0.5 t/ha for unimproved local varieties. For groundnut, IAR targets pod yield, shelling percentage, and hundred-seed weight. Days to maturity is a yield-related trait of particular importance in Nigeria because early maturity allows escape from terminal drought and enables double-cropping within the growing season.

Fill in the blank: In cereals, _____ index (the ratio of grain weight to total above-ground biomass) is used as a selection criterion for high-yielding varieties; NCRI targets a harvest index

above 0.50 in improved rice varieties to ensure that a large proportion of photosynthate is partitioned into the harvestable grain.

5.1.2 Quality traits in Nigerian crops

Quality traits determine the economic and nutritional value of the crop beyond yield. Processing quality traits for cassava include: dry matter content (high dry matter gives higher gari and fufu yield per kilogram of fresh root; targeted above 30 percent at IITA); hydrogen cyanide content (HCN; low HCN is essential for food safety in fresh-consumption and baby food varieties; bitter varieties with high HCN are preferred by some processors but require thorough fermentation); starch quality (amylose:amylopectin ratio affects starch functionality for industrial use). For maize, kernel quality traits include: protein content and amino acid profile (Quality Protein Maize, QPM, developed by CIMMYT and introduced through IITA into Nigeria, carries the opaque-2 gene that doubles lysine and tryptophan content, addressing protein deficiency); oil content; and milling quality.

Nutritional quality improvement is increasingly important in Nigerian crop breeding. Biofortification is the process of increasing the content of micronutrients (vitamins, minerals) in crop staples through breeding. IITA has developed provitamin A cassava varieties (orange-fleshed; carotenoid content above 10 micrograms per gram fresh weight; HarvestPlus programme) and high-iron and zinc cowpea varieties (IT97K series). NCRI has introduced vitamin A-enriched orange maize into Nigeria. IAR has selected high-oleic groundnut lines with improved oil quality for the edible oil market. Grain texture (hardness), taste, and cooking time are quality traits evaluated by consumer panels and must be acceptable to Nigerian consumers for a variety to be adopted, regardless of its yield performance.

Fill in the blank: _____ is the breeding-based process of increasing the content of vitamins and minerals in staple crops; an example in Nigeria is the development of orange-fleshed provitamin A cassava varieties by IITA under the HarvestPlus programme.

5.1.3 Adaptation traits: drought, heat, and soil stress tolerance

Abiotic stress tolerance is critical for sustainable crop production in Nigeria's variable and changing climate. Drought tolerance in maize is quantified by the Drought Tolerance Score (DTS: days to silking under stress minus days to silking under well-watered conditions; lower DTS indicates less stress sensitivity) and by the Anthesis-Silking Interval (ASI: number of days between anthesis and silking; a short ASI under drought indicates synchrony of male and female flowering and is positively correlated with grain set and yield under stress). IITA has released drought-tolerant maize varieties for Nigeria (DTMA varieties) using these selection criteria under managed drought stress at research stations in Ikenne and Kano.

Aluminium toxicity and low soil phosphorus availability are major soil constraints in the acid soils of southern Nigeria (forest zone; Guinea savanna on weathered soils). Cassava and cowpea show natural tolerance; maize varieties developed at IITA have been selected for performance on acid soils. Heat tolerance is increasingly important as mean temperatures rise; selection criteria include pollen viability at high temperature, stomatal conductance, and canopy temperature depression under heat stress. Waterlogging tolerance is important in the Niger Delta and riverine areas; cassava root rot under waterlogged conditions is a major problem; selection for field tolerance in waterlogged trial plots is practised at IITA. Striga resistance (resistance to Striga hermonthica and S. gesnerioides, parasitic weeds causing 30 to 80 percent yield loss in Nigerian cereals and legumes) is bred through soil incorporation screening at IAR Zaria and IITA.

Fill in the blank: The Anthesis-Silking Interval (ASI) is used as a selection criterion for drought tolerance in maize; a short _____ under drought stress indicates synchronised male and female flowering, which is positively associated with grain set and yield under water deficit.

Pilot questions 5.1

- State the four yield components of cassava and explain which is most important for processing quality.
- Define biofortification and give two examples of biofortified crop varieties released in Nigeria.

- Explain how the Anthesis-Silking Interval (ASI) is used as a selection criterion for drought tolerance in maize.
- Name two abiotic soil stress constraints in southern Nigeria and state the crop most affected by each.
- Why must quality traits such as taste and cooking time be evaluated alongside yield in Nigerian crop breeding?

5.2 Desired Traits in Animal Improvement

5.2.1 Productivity traits in Nigerian livestock

Productivity traits directly determine the economic output of a livestock enterprise. In dairy cattle, the primary traits are total milk yield per lactation (litres), peak milk yield, and lactation length; secondary traits include milk fat percentage and protein percentage. Unimproved White Fulani cows produce 400 to 800 litres per lactation; NAPRI-developed Friesian x Fulani crosses produce 2,000 to 4,000 litres under intensive management. In beef cattle, sheep, and goats, growth rate (average daily gain, ADG in g/day), feed conversion ratio (FCR: kg feed per kg gain), and final body weight at market age are the primary selection traits. Litter size and litter weight at weaning are the key productivity traits for Nigerian village pigs; NVRI Vom targets litter sizes of 8 to 10 for improved Landrace x Large White crosses.

In poultry, the primary productivity traits differ between layers and broilers. For layers: egg number per hen housed per year (HH; targeted above 250 for commercial layers); egg weight (g; 55 to 65 g for brown egg layers); and feed conversion efficiency. For broilers: body weight at 6 weeks (targeted above 2.0 kg for commercial broilers); feed conversion ratio (targeted below 2.0); breast meat yield percentage; and livability. In aquaculture (Clarias catfish, Oreochromis niloticus tilapia in Nigeria), growth rate to market size, feed conversion, and disease resistance are the primary selection traits. FUNAAB and the National Institute for Freshwater Fisheries Research (NIFFR, New Bussa) conduct selective breeding for growth rate in Clarias gariepinus and tilapia.

Fill in the blank: In Nigerian poultry layer improvement, the primary productivity trait is egg number per hen _____ (HH) per year; commercial layer breeds target above 250 eggs per hen housed per year under good management conditions.

5.2.2 Adaptation and fitness traits in Nigerian livestock

Adaptation traits determine whether an animal can survive and reproduce effectively under the environmental conditions of its production system. In Nigeria, the most important adaptation traits are: heat tolerance (ability to maintain feed intake, growth rate, and reproduction under high ambient temperature and solar radiation; assessed by rectal temperature under heat stress, respiratory rate, and production maintenance); trypanotolerance (haematocrit maintenance under trypanosome challenge; described in Series 4); tick resistance (the ability to maintain low tick burdens under natural tick challenge; important for disease transmission and production impact; local zebu breeds show higher tick resistance than exotic taurine breeds); and drought tolerance in range livestock (ability to maintain body condition on sparse, dry-season pasture).

Reproductive efficiency traits are key fitness traits: age at first calving or lambing (AFC; shorter AFC improves lifetime productivity); calving or lambing interval (CI; shorter interval means more calves or lambs per lifetime); conception rate; and neonatal survival. In Nigerian cattle, AFC for improved Friesian x Fulani crosses is 28 to 36 months, compared with 36 to 48 months for unimproved White Fulani, reflecting the trade-off between growth rate and age at maturity. In small ruminants (WAD goats, Yankasa sheep), high prolificacy (twinning rate) is a selection objective at NAPRI because it directly multiplies annual output per breeding female. Body condition score (BCS) is a practical field assessment of energy reserves that is correlated with reproductive performance and health status in all species.

Fill in the blank: _____ condition score (BCS) is a hands-on assessment of an animal's subcutaneous fat and muscle cover, scored on a 1 to 5 scale in cattle; it is used as a management and breeding tool because it predicts reproductive performance, milk yield, and resistance to metabolic disease.

5.2.3 Carcass and product quality traits

Carcass quality traits are evaluated at slaughter and determine the value of the animal in the meat market. Key traits include: dressing percentage (carcass weight as a percentage of live weight; typically 48 to 55 percent for improved cattle; 45 to 50 percent for local zebu); eye muscle area (longissimus dorsi cross-section; positively correlated with lean meat yield); backfat thickness (negatively correlated with lean yield; measured ultrasonically in live pigs and cattle in modern programmes); meat tenderness (Warner-Bratzler shear force; positively associated with consumer acceptance; influenced by myosin heavy chain isoforms and calpain activity); and meat colour and water-holding capacity.

In poultry, breast meat percentage (proportion of carcass weight as breast meat), skin colour, and fat content are evaluated. For dairy cattle, milk fat percentage (targeted 3.5 to 4.5 percent for Holstein-Friesian breeds) and milk protein percentage (targeted 3.2 to 3.5 percent) are key quality traits affecting processing yield for butter and cheese production; somatic cell count (SCC) is an inverse indicator of udder health. In aquaculture, fillet yield, flesh colour (important for tilapia in export markets), and texture are quality traits selected in advanced Nigerian aquaculture breeding programmes. NAPRI and FUNAAB use ultrasound scanning to estimate backfat thickness and eye muscle area in live cattle and pigs without slaughter.

Fill in the blank: _____ percentage, the ratio of carcass weight to live weight expressed as a percentage, is a key carcass quality trait in beef cattle; improved Friesian x Fulani crosses typically achieve 48 to 55 percent dressing percentage, compared with 45 to 50 percent for unimproved local zebu.

5.3 Practical Breeding Operations

5.3.1 Crossing techniques in plants

Controlled crossing in plants requires preventing self-pollination of the seed parent and ensuring that the desired pollen parent is the only source of pollen. The procedure for hand-pollination in hermaphrodite crops (e.g. cowpea, maize, sorghum): (1) emasculation: remove anthers from the seed parent flower before pollen is shed, either by hand (tweezers; used in cowpea, sorghum,

pearl millet) or by hot water treatment (submerging the flower head in hot water at 40 to 45 degrees C for 10 minutes; used in rice); (2) bagging: cover the emasculated flower or floret with a glassine bag or paper bag to prevent contamination with foreign pollen until the stigma is receptive; (3) pollination: when the stigma is sticky and receptive (typically 24 to 48 hours after emasculation), remove the bag, dust pollen collected from the desired pollen parent onto the stigma, and re-bag; (4) labelling: tag the crossed flower with a label recording the cross code, date, and seed and pollen parent identities.

For maize specifically: pollen is collected by placing a bag over the tassel the evening before, securing it in the morning when pollen is shed and transferring it immediately to the de-tasselled silk of the seed parent. In self-incompatible crops (Brassica species), compatible crosses between two SI lines can be made simply by placing the lines adjacent in a crossing block; emasculation is not needed. In wide crosses between incompatible species, in vitro pollination (placing pollen directly on the cut style surface) may be used to bypass style incompatibility. Quality control in crossing includes confirming successful fertilisation by checking for fruit set, recording cross numbers and parental identities in the crossing register, and verifying putative hybrid genotype by molecular markers.

Fill in the blank: In controlled crossing of cowpea and sorghum, _____ is the removal of anthers from the seed parent flower before pollen is shed; it prevents self-pollination and ensures that all seed set on the seed parent results from cross-pollination with the designated pollen parent.

5.3.2 Controlled mating and reproductive technologies in animals

Controlled mating in animals ensures that specific sires are mated with specific dams, enabling accurate pedigree recording and breeding value estimation. Methods include: hand mating (a specific bull, ram, or boar is introduced to a specific female at the time of oestrus and removed after mating; both parent identities are recorded); pen mating with individual sire recording (a single sire is placed with a group of females for a fixed mating period; paternity is known); and artificial insemination (AI; semen is collected from a selected sire, evaluated for quality,

processed, and introduced into the female's reproductive tract manually; allows one sire to serve many females; semen from superior sires can be stored frozen for years).

Reproductive technologies available at NAPRI and advanced university farms in Nigeria include: semen evaluation (motility, morphology, concentration assessed before use); semen cryopreservation (extended in egg-yolk citrate or Tris-based extender; cooled to -196 degrees C in liquid nitrogen; stored in 0.25 ml straws); oestrus synchronisation (PGF2-alpha injection or progesterone-releasing intravaginal device, PRID, synchronises oestrus for AI to allow timed AI without heat detection); superovulation (FSH treatment stimulates multiple ovulations); embryo collection (flushing the uterus with saline to recover multiple embryos from a superovulated donor); and embryo transfer (ET; placing recovered embryos into synchronised recipient females). IVF (in vitro fertilisation) and ICSI (intracytoplasmic sperm injection) are available at research level at some Nigerian universities.

Fill in the blank: In Nigerian cattle AI programmes, semen from selected bulls is extended in an egg-yolk based extender, cooled, and stored at _____ degrees C in liquid nitrogen in 0.25 ml straws; it can remain viable for decades, allowing distribution of superior sire genetics nationwide.

5.3.3 Progeny evaluation and variety or breed testing

Progeny evaluation determines whether a candidate variety (in plants) or breeding animal (in livestock) performs as well as or better than existing standards when grown or raised by farmers under realistic conditions. In crop breeding, the stages are: preliminary yield trials (PYT; first evaluation of a large number of advanced lines in replicated plots at one or two sites); advanced yield trials (AYT; a smaller number of lines evaluated at more sites); national performance trials (NPT; final evaluation across all agro-ecological zones under NVRC oversight before variety release). Statistical analysis uses ANOVA, BLUP, or mixed-model approaches to separate genetic from environmental effects and identify stable, high-performing lines. GxE (genotype by environment) interaction analysis identifies lines with wide adaptation vs specific adaptation.

In animal breeding, progeny testing evaluates a sire by measuring performance of his daughters or sons under defined conditions. The accuracy of a progeny test increases with the number of

progeny evaluated: at least 20 to 30 daughters are recommended for reliable milk yield EBV estimation in dairy bulls. Contemporary comparison methods (comparing daughters with unrelated contemporaries raised at the same farm and time) control for environmental differences between herds. NAPRI conducts progeny testing of White Fulani bulls using daughter records from both station and on-farm herds. Genomic estimated breeding values (GEBVs) are increasingly replacing traditional progeny testing in countries with SNP-chip resources; ILRI supports GEBV estimation for West African trypanotolerant cattle breeds using its 10K chip.

Fill in the blank: In crop variety testing, the final multi-site evaluation carried out across all Nigerian agro-ecological zones before NVRC variety release approval is called the National _____ Trial (NPT); it determines whether a candidate variety consistently outperforms existing check varieties for yield, disease resistance, and quality.

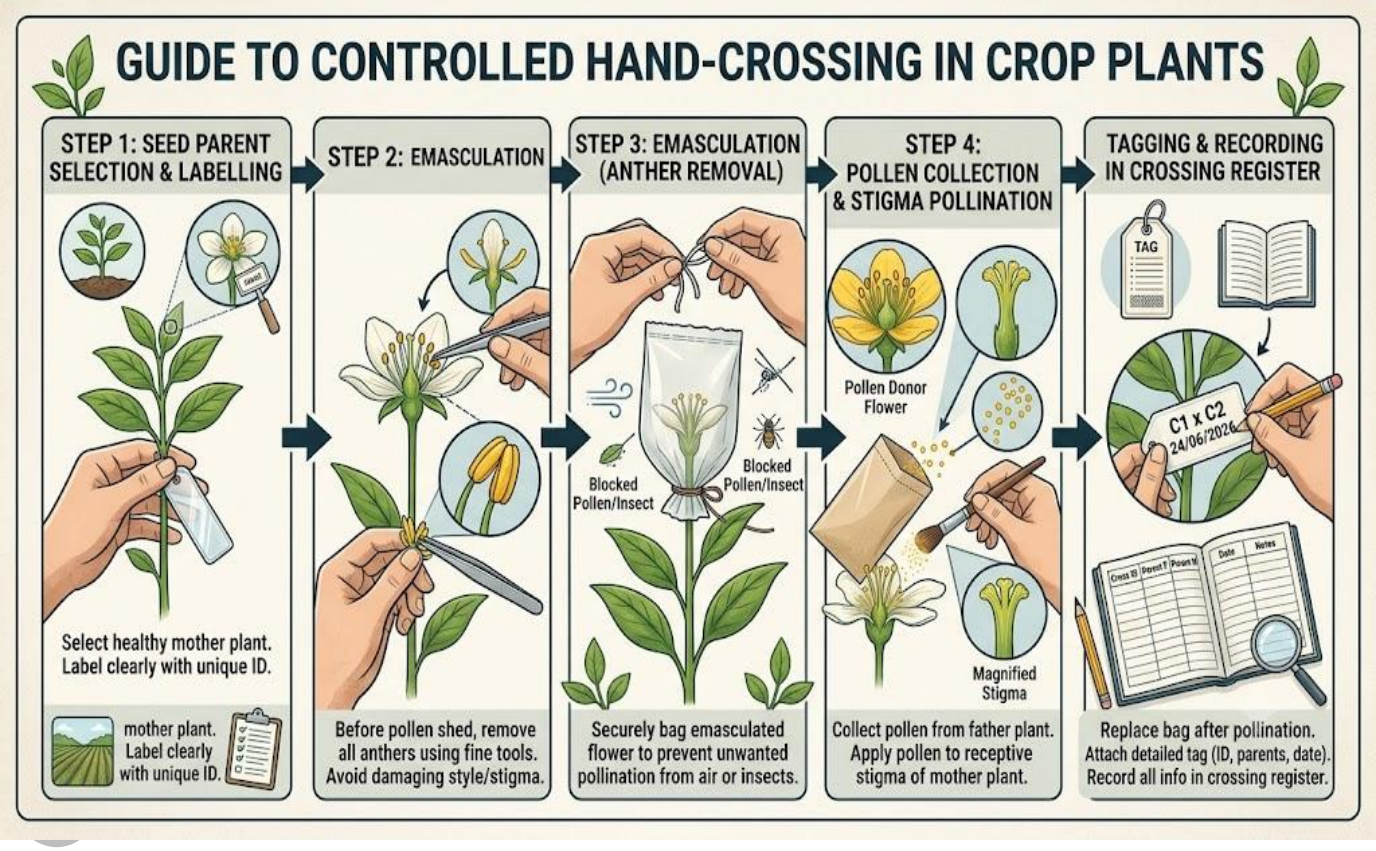

Figure 5.1: Stepwise procedure for controlled hand-crossing in crop plants

Pilot questions 5.3

- Describe the four steps of hand-crossing in cowpea and explain why emasculation is necessary.
- Explain the difference between hand mating and artificial insemination in Nigerian cattle breeding.
- Describe how oestrus synchronisation is used to improve the efficiency of AI programmes in cattle.
- Explain the difference between preliminary yield trials (PYT) and national performance trials (NPT) in Nigerian crop variety testing.
- Why is progeny testing preferred over individual selection for estimating the breeding value of a bull for milk yield?

5.4 Farm Record Keeping in Breeding Programmes

5.4.1 Importance and types of farm records

Farm records are the systematic documentation of all activities, events, and measurements related to crops and animals on a farm or research station. In breeding programmes, accurate records are indispensable because: they provide the performance data needed to calculate breeding values and estimate genetic parameters; they enable tracking of genetic progress over generations; they allow identification of superior individuals, families, and populations; they document pedigree relationships needed for relationship matrix construction; and they support regulatory requirements for variety registration (NASC, NVRC) and breed certification. Without records, a breeding programme is reduced to guesswork: the breeder cannot know whether selection is working, which parents contributed most to progress, or what the rate of inbreeding is.

Types of records maintained in plant breeding: crossing records (parents, cross date, cross number, number of seeds obtained); field books (plot identity, treatment, germination, stand count, disease score, yield per plot); phenotyping records (all measured traits per individual plant or plot per season and location); pedigree records (parentage of each line traceable to the original

cross); seed inventory (seed lots, quantities, storage conditions, germination tests); and release dossiers (all trial data submitted for NVRC approval). Types of records in animal breeding: pedigree records (sire, dam, date of birth, breed, farm identity); production records (milk yield per milking or per lactation; litter size and litter weight; egg number; growth rate); health records (disease episodes, treatments, vaccinations); reproductive records (oestrus dates, mating dates, pregnancy diagnoses, calving/lambing/farrowing dates, neonatal survival); and slaughter records (live weight, carcass weight, carcass quality measurements).

Fill in the blank: In animal breeding, _____ records document the sire, dam, date of birth, breed composition, and farm identity of each animal; they are the foundation of breeding value estimation because they define the genetic relationships among individuals in the population.

5.4.2 Recording systems for plant breeding programmes

Plant breeding recording systems organise data collected across multiple seasons, locations, and generations. A crossing register is a hardcover book or spreadsheet in which each cross is assigned a unique code (e.g. IITA-CB-2024-001), recording the female parent identity, male parent identity, date of crossing, number of F1 seeds obtained, and germination date. F2 and subsequent generation field books record: plot number; row number; genotype code; stand count; flowering date; disease score at each assessment; and plot yield at harvest. All data must be referenced to the trial design (alpha-lattice, augmented design, p-rep design) and management factors (season, year, location, fertiliser treatment) to allow valid statistical analysis.

Modern plant breeding programmes use electronic data capture tools: FieldBook app (open-source Android application developed by Breeding Management System, BMS project; widely used at IITA and NCRI) allows data entry directly on tablets in the field with GPS geo-referencing of plots; data are automatically uploaded to a central database. The Breeding Management System (BMS) developed by the Generation Challenge Programme (now integrated into CGIAR) is a web-based database platform used by IITA and partner institutions for managing crossing records, trial designs, pedigree data, and phenotypic and genotypic data for cassava, maize, cowpea, and other crops. Data backup (daily to a cloud server or external hard drive) is essential; loss of multi-season trial data represents an irreplaceable scientific setback.

Fill in the blank: The _____ app is an open-source Android application used by IITA and NCRI breeders to capture field phenotyping data directly on tablets in the field, with GPS referencing of plots, replacing handwritten field books and reducing transcription errors.

5.4.3 Recording systems for animal breeding programmes

Animal breeding recording systems must capture data on all production, reproduction, and health events for each individual animal throughout its lifetime. The minimum dataset for a cattle breeding station record system includes: animal identity (RFID ear tag or tattoo number); dam and sire identity; date of birth; birth weight; weaning weight and date; all subsequent body weights with dates; first calving date; calving interval; milk yield per test-day (at least monthly; test-day model analysis gives more accurate EBVs than lactation-total models); calving ease scores; disease events with dates and treatments; and disposal date and reason (sale, death, culling). NAPRI Shika uses a paper-based animal record system supplemented by Microsoft Excel databases; the transition to dedicated livestock management software (INTERHERD; DairyComp305; BREED) is ongoing.

The National Animal Production Research Institute (NAPRI) publishes annual herd performance summaries based on station records, which serve as the national reference for White Fulani, Bunaji, N'Dama, Muturu, and Red Bororo cattle performance under Nigerian conditions. For small ruminants, ABU and FUNAAB maintain flock record books with individual ewe/doe cards recording mating date, kidding/lambing date, litter size, birth weight, weaning weight, and post-weaning growth. In commercial poultry farms, weekly production records (eggs per flock, feed consumed, mortality rate, body weight samples) are the standard management tool; breeding farms additionally record individual hen identity, egg number per hen, fertility, and hatchability. RFID (radio frequency identification) ear tags, electronic milk meters, and automated weighing systems are increasingly deployed in Nigerian teaching and research farms to reduce the labour and error associated with manual recording.

Fill in the blank: _____ (Radio Frequency Identification) ear tags allow each animal to be uniquely identified electronically; when linked to automatic weighing platforms or milk meters,

they enable continuous, labour-efficient capture of individual performance data without manual recording errors.

Record Type	Key Information Captured
Crossing Register	Parent lines used, date of cross, method of pollination, cross ID
Field Book	Plot layout, agronomic traits, yield data, pest/disease scores
Pedigree (Plants)	Lineage of varieties, ancestry of crosses, genetic background
Seed Inventory	Seed lot ID, quantity, storage conditions, viability status
Pedigree (Animals)	Lineage of sire and dam, ancestry, breed composition
Production Records	Growth rate, milk yield, egg production, weight gain
Health Records	Vaccinations, disease incidence, treatments, mortality
Reproductive Records	Breeding dates, conception rates, litter size, calving/kidding intervals
Carcass Records	Slaughter weight, dressing percentage, meat quality traits

Box 5.1: Standard record types for plant and animal breeding programmes in Nigeria

Pilot questions 5.4

1. State four types of records kept in a plant breeding programme and the information each contains.
2. Explain why accurate pedigree records are essential for calculating breeding values in animal breeding.
3. Describe how the FieldBook app improves data capture in Nigerian crop breeding field trials.
4. State five categories of data recorded for each individual cattle at NAPRI Shika.
5. Explain the consequence of losing multi-season trial data in a crop breeding programme.

Series Summary

Desired traits in Nigerian crop improvement include higher yield, better quality, and tolerance to environmental stress. Important yield traits include grain number, grain weight, and harvest index in cereals, as well as root number, fresh weight, and dry matter content in cassava. Quality traits include low hydrogen cyanide, improved starch quality, higher lysine and tryptophan in quality protein maize, and biofortification with provitamin A, iron, and zinc. Stress-tolerance traits include drought tolerance, measured through indicators such as anthesis-silking interval and days to silking, as well as resistance to Striga, aluminium toxicity, and low-phosphorus soils. In livestock, desired traits include milk yield, average daily gain, feed conversion ratio, litter size, egg production, heat tolerance, trypanotolerance, tick resistance, body condition score, dressing percentage, eye muscle area, backfat thickness, and milk fat and protein content. Practical breeding operations include emasculation, bagging, hand-pollination, labelling, and keeping crossing registers in plants, while animals are bred through hand mating, artificial insemination, semen cryopreservation at **−196°C**, timed insemination, oestrus synchronisation, superovulation, embryo collection, and embryo transfer.

Progeny evaluation in crops involves preliminary yield trials, advanced yield trials, and national performance trials, while livestock improvement uses progeny testing and genomic estimated breeding values. Farm record keeping is essential because it provides performance data for breeding-value estimation, tracks genetic progress, confirms pedigree relationships, and supports variety and breed registration. Plant breeding records include crossing registers, field books, pedigree records, and seed inventories, with tools such as FieldBook and Breeding Management System software used at institutions like IITA and NCRI. Animal breeding records cover pedigree, production, health, reproduction, and carcass performance, while NAPRI Shika maintains national performance records for White Fulani and N'Dama cattle. RFID tags and automated sensors are also improving the accuracy and efficiency of livestock data collection in Nigerian research stations.

Glossary of Terms

1. **Anthesis-Silking Interval (ASI):** the number of days between anthesis (pollen shed) and silking (silk emergence) in maize; a short ASI under drought stress indicates tolerance and is positively correlated with grain set.
2. **Biofortification:** the process of increasing the content of vitamins or minerals in staple crops through plant breeding; examples include provitamin A cassava and high-iron cowpea developed by IITA under the HarvestPlus programme.
3. **Body Condition Score (BCS):** a hands-on assessment of subcutaneous fat and muscle cover in livestock, scored on a 1 to 5 scale (cattle) or 1 to 9 scale (poultry); used to assess energy reserves and predict reproductive performance.
4. **Breeding Management System (BMS):** a web-based platform used at IITA and partner institutions for managing pedigree, crossing, trial design, and phenotypic and genotypic data in crop breeding programmes.
5. **Crossing register:** a written or electronic record of all crosses made in a plant breeding programme, recording cross code, seed parent, pollen parent, date, and number of F1 seeds obtained.
6. **Dressing percentage:** carcass weight expressed as a percentage of live slaughter weight; a key carcass quality trait; typically 48 to 55 percent for improved beef cattle and 45 to 50 percent for Nigerian local zebu breeds.
7. **Emasculation:** the removal of anthers from a flower before pollen shed to prevent self-fertilisation; the first step in controlled plant crossing; performed by tweezers (cowpea, sorghum) or hot water (rice).
8. **FieldBook app:** an open-source Android application for capturing field phenotyping data on tablets with GPS referencing; used by IITA and NCRI to replace handwritten field books and reduce transcription errors.
9. **Harvest index:** the ratio of grain or economic yield to total above-ground biomass; a measure of the efficiency of partitioning photosynthate into the harvestable product; targeted above 0.50 in improved Nigerian rice varieties.
10. **National Performance Trial (NPT):** the final multi-site yield trial conducted across all Nigerian agro-ecological zones before NVRC variety release approval; determines wide adaptation and consistency of performance.

11. **Oestrus synchronisation:** the use of hormonal treatments (PGF2-alpha injection or PRID) to synchronise the timing of oestrus in groups of females, enabling timed AI without the need for individual heat detection.
12. **Quality Protein Maize (QPM):** maize carrying the opaque-2 gene, which doubles lysine and tryptophan content relative to normal maize; developed by CIMMYT and introduced into Nigerian varieties through IITA; addresses protein malnutrition.
13. **RFID (Radio Frequency Identification):** electronic identification technology using microchip-embedded ear tags that communicate with scanners; enables automated individual animal identification and links to milk meters and weighing systems for labour-efficient data capture.
14. **Superovulation:** hormone treatment (FSH injections) of a donor female to stimulate multiple ovulations; used in embryo transfer programmes to recover multiple embryos from a genetically superior dam.
15. **Test-day model:** a statistical model for estimating breeding values for milk yield using individual test-day records (monthly measurements) rather than lactation totals; more accurate because it models the lactation curve and accounts for days in milk.

Concept Check Questions [Series 5]

Objective Questions

1. The ratio of grain weight to total above-ground biomass, used as a selection criterion for yield efficiency in rice improvement, is called the _____ index. (Linked to SLO 5.1)
2. The breeding-based process of increasing vitamin and mineral content in staple crops is called _____; an example is provitamin A cassava developed by IITA. (Linked to SLO 5.1)
3. The removal of anthers from a flower before pollen shed to prevent self-fertilisation in a crossing programme is called _____. (Linked to SLO 5.3)

4. Semen from selected bulls is stored in liquid nitrogen at _____ degrees C in 0.25 ml straws for distribution in AI programmes. (Linked to SLO 5.3)
5. The final multi-site crop variety evaluation across all Nigerian agro-ecological zones required before NVRC release approval is called the National _____ Trial. (Linked to SLO 5.4)

Short-Answer Questions

1. State three yield components of maize and explain why they have higher heritability than yield itself. (Linked to SLO 5.1)
2. Describe three productivity traits targeted in Nigerian dairy cattle improvement. (Linked to SLO 5.2)
3. Describe the four steps of hand-crossing in sorghum. (Linked to SLO 5.3)
4. State four types of records kept in an animal breeding programme and the information each captures. (Linked to SLO 5.5)
5. Explain how the FieldBook app improves data capture in Nigerian crop breeding programmes. (Linked to SLO 5.6)

Long-Answer Questions

- Describe the principal yield, quality, and stress tolerance traits targeted in Nigerian crop improvement, with examples from cassava, maize, and cowpea breeding. (Linked to SLO 5.1)
- Describe the desired productivity, adaptation, and carcass quality traits in Nigerian livestock improvement. Explain the practical crossing and controlled mating operations used in Nigerian plant and animal breeding. (Linked to SLOs 5.2, 5.3)
- Explain the importance of farm record keeping in breeding programmes. Describe the recording systems used in Nigerian plant and animal breeding, including the role of digital tools. (Linked to SLOs 5.5, 5.6)

Answers to Concept Check Questions [Series 5]

Objective Questions

1. Harvest.
2. Biofortification.
3. Emasculation.
4. -196.
5. Performance.

Short-Answer Questions

6. Yield components: grain number per panicle; grains per cob; individual grain weight. Higher heritability than yield because they are less influenced by genotype x environment interaction; yield integrates all environmental effects across the whole season, whereas individual components reflect shorter developmental windows that are more genetically determined.
7. Total milk yield per lactation (litres); peak milk yield; lactation length. Secondary: milk fat percentage and milk protein percentage.
8. Emasculate seed parent spikelets before pollen shed using tweezers or hot water (40 to 45 degrees C, 10 minutes). Bag emasculated panicle with glassine bag. Collect pollen from pollen parent panicle when mature. Apply pollen to receptive seed parent stigma; re-bag. Label with cross code, date, and parent identities.
9. Pedigree record (animal ID, sire, dam, birth date, breed). Production record (milk yield, litter size, growth rate, egg number). Health record (disease events, treatments, vaccinations). Reproductive record (mating date, calving/lambing date, litter size, neonatal survival).
10. FieldBook app allows data entry directly on tablets in the field with GPS geo-referencing of plots; data automatically uploaded to central database; eliminates handwritten transcription; reduces entry errors; allows real-time data backup; used at IITA and NCRI.

Long-Answer Questions

11. Cassava: yield components (root number, fresh weight, dry matter content above 30 percent, harvest index above 0.65); quality (low HCN for fresh consumption; starch quality for industry; provitamin A carotenoid above 10 micrograms per gram in

biofortified varieties at IITA). Maize: yield components (panicle number, grains per cob, grain weight); quality (QPM opaque-2 gene; lysine and tryptophan content; milling quality; provitamin A orange maize at NCRI); drought tolerance via ASI and DTS selection at Ikenne and Kano DTMA trials. Cowpea: yield components (pods per plant, seeds per pod, seed weight); quality (high-iron and zinc IT97K series for biofortification); Striga resistance (soil incorporation screening at IITA); early maturity for double-cropping in Guinea savanna. Abiotic stresses: drought tolerance (short ASI in maize); aluminium toxicity and low-P tolerance (acid soils in southern Nigeria; cassava and cowpea naturally tolerant; selected maize lines at IITA); waterlogging (Niger Delta; cassava root rot resistance at IITA).

12. Productivity traits: dairy cattle (milk yield 400 to 800 litres/lactation unimproved White Fulani; 2,000 to 4,000 litres NAPRI Friesian x Fulani crosses; peak yield; lactation length; fat and protein percent); beef/sheep/goat (ADG, FCR, final body weight); pigs (litter size 8 to 10, litter weaning weight; NVRI Vom); poultry layers (egg number per HH above 250; egg weight 55 to 65 g); broilers (6-week body weight above 2.0 kg; FCR below 2.0). Adaptation traits: heat tolerance; trypanotolerance; tick resistance; drought tolerance; reproductive efficiency (AFC, CI, twinning rate); BCS. Carcass quality: dressing percentage (48 to 55 percent improved cattle); eye muscle area; backfat thickness (ultrasound); tenderness; milk fat and protein percent. Practical crossing in plants: select seed parent; emasculate; bag; collect and apply pollen; label. Controlled mating in animals: hand mating (specific sire x dam; records both); AI (semen collected, evaluated, extended, cryopreserved at -196 degrees C; distributed in straws; oestrus synchronised with PGF2-alpha or PRID for timed AI; NAPRI national AI centre). ET: superovulation with FSH; embryo collection by uterine flushing; transfer to synchronised recipients. Progeny evaluation: PYT, AYT, NPT for crops (NVRC approval); progeny testing (minimum 20 to 30 daughters for bulls; NAPRI White Fulani programme) or GEBV from ILRI 10K chip for cattle.
13. Importance: performance data for breeding value estimation; tracking genetic progress; pedigree for relationship matrix; regulatory compliance (NASC, NVRC). Plant records: crossing register (cross code, parents, date, seeds); field book (plot ID, stand, disease score, yield per plot per season); pedigree record (parentage traceable to original cross);

seed inventory (lot, quantity, germination). FieldBook app: tablet-based data entry in field; GPS geo-referencing; automatic upload to BMS database; reduces transcription error; used at IITA and NCRI. BMS platform: web-based; manages crossing, trial design, pedigree, phenotypic and genotypic data for cassava, maize, cowpea. Animal records: pedigree (animal ID, sire, dam, birth date, breed); production (milk yield, litter size, growth rate, egg number); health (disease, treatments, vaccines); reproductive (mating, calving dates, litter size, neonatal survival); carcass (live weight, carcass weight, dressing percent, eye muscle area). NAPRI Shika: paper + Excel database for White Fulani, N'Dama, Muturu station herds; publishes annual performance summaries as national reference. RFID tags: electronic individual ID; linked to automatic weighing and milk meters for labour-efficient continuous data capture; deployed at NAPRI, FUNAAB, and ABU research herds.

Answers to Pilot Questions [Series 5]

Part 5.1

1. Yield components of cassava: root number per plant; average root diameter and length; root fresh weight per plant; dry matter content. Most important for processing quality: dry matter content (percentage starch); high dry matter gives greater gari and fufu yield per kilogram of fresh root.
2. Biofortification: the breeding-based increase of micronutrient content in staple crops. Examples: (1) Provitamin A cassava (orange-fleshed; above 10 micrograms per gram; developed by IITA HarvestPlus). (2) High-iron and zinc cowpea (IT97K series; IITA).
3. ASI = days from anthesis (pollen shed) to silking (silk emergence). Under drought stress, silk emergence is delayed more than anthesis, widening ASI. A short ASI under drought indicates synchronised flowering, associated with more successful pollination and grain set. Breeders select for short ASI under managed drought stress at IITA stations in Ikenne and Kano.
4. Aluminium toxicity: affects maize and some legumes on weathered acid soils of southern Nigeria; low soil pH releases toxic Al3+ ions that inhibit root growth. Low soil

phosphorus availability: affects most crops on highly weathered Ultisols and Oxisols of the forest zone; cassava and cowpea show natural tolerance.

5. A variety with high yield but unacceptable taste, long cooking time, or unappealing texture will be rejected by farmers and consumers regardless of agronomic performance. Adoption depends on both yield and consumer acceptance; varieties must satisfy end-user quality requirements to be taken up and grown at scale.

Part 5.2

6. Total milk yield per lactation (litres); peak milk yield (litres/day); lactation length (days); milk fat percentage; milk protein percentage.
7. Heat tolerance: animal maintains feed intake, growth, and reproduction under high ambient temperature; assessed by rectal temperature and respiratory rate under heat stress. Trypanotolerance: haematocrit maintenance under trypanosome infection without drug treatment; N'Dama and WAD breeds. Tick resistance: ability to maintain low tick burdens under natural challenge; local zebu breeds more resistant than exotic taurine breeds.
8. Dressing percentage (carcass weight as percent of live weight; 48 to 55 percent improved cattle). Eye muscle area (longissimus dorsi cross-section; indicates lean yield). Backfat thickness (measured by ultrasound; inversely related to lean yield). Meat tenderness (Warner-Bratzler shear force; consumer acceptance).
9. ADG (average daily gain in g/day): measures growth rate from birth to market weight. FCR (feed conversion ratio: kg feed per kg liveweight gain): measures feed efficiency; lower is better. Final body weight at market age: determines carcass value.
10. AFC (age at first calving): shorter AFC increases lifetime productivity. CI (calving interval): shorter interval gives more calves per cow lifetime. Conception rate: proportion of females conceiving at first service. Neonatal survival: proportion of calves alive at weaning.

Part 5.3

11. (1) Select seed parent plant; label it. (2) Emasculate: remove anthers from cowpea flower bud before pollen shed using forceps; bag the emasculated flower. (3) Pollinate: collect pollen from pollen parent; apply to receptive stigma of emasculated flower 24 to 48 hours

later; re-bag. (4) Label: attach tag with cross code, date, seed parent, and pollen parent identities. Emasculation is necessary to prevent self-pollination of the seed parent, ensuring all seeds set result from the desired cross.

12. Hand mating: specific sire introduced to specific female at oestrus; both identities recorded; paternity certain; labour-intensive for large herds. AI: semen collected from selected sire; processed, extended, and cryopreserved; deposited in female reproductive tract manually; one sire serves many females; distributes superior genetics widely; requires oestrus detection or synchronisation.
13. Oestrus synchronisation using PGF2-alpha injection (or PRID progesterone device) aligns oestrus of groups of females within a 48 to 72-hour window. Timed AI is performed at a fixed time after synchronisation treatment without individual heat detection. This allows all females in a group to be inseminated in one operation, reducing labour, ensuring accurate mating dates, and enabling batch calving management.
14. PYT (Preliminary Yield Trial): large number of advanced lines (100 to 200); 1 to 2 locations; one replicate or small plots; identifies promising lines for advancement; eliminates poor performers. NPT (National Performance Trial): small number of elite lines (10 to 20); all agro-ecological zones; multiple replications; multi-year; determines wide adaptation and stable performance; required for NVRC variety release.
15. Bulls cannot be evaluated directly for milk yield (they do not produce milk). Progeny testing uses daughter records; each daughter's performance reflects half the sire's additive gene effects plus environmental effects; averaging across 20 to 30 daughters removes most environmental variation and gives a reliable estimate of the sire's breeding value for milk yield.

Part 5.4

1. Crossing register (cross code, parents, date, seeds obtained). Field book (plot identity, stand count, disease scores, yield per plot). Pedigree record (parentage of each line traceable to original cross). Seed inventory (lot number, quantity, storage conditions, germination percentage).
2. Breeding value estimation (BLUP) requires a relationship matrix constructed from pedigree; without accurate sire-dam identities for each animal, the matrix is wrong and

EBVs are unreliable. Pedigree records also allow calculation of the inbreeding coefficient (F) to monitor and manage inbreeding in small herds.

3. FieldBook app: data entered on Android tablet in the field as each plot is assessed; GPS coordinates automatically recorded with each entry; data uploaded to BMS database at end of day; eliminates handwritten field books and post-season transcription; reduces errors; allows immediate data quality checks; backup to cloud prevents data loss.
4. Animal identity (RFID number or ear tag). Dam and sire identity with dates. Birth weight and subsequent body weights with dates. Milk yield per test-day (monthly). Disease events with dates, treatment, and outcomes.
5. Multi-season trial data represent years of scientific work and investment; once lost it cannot be reconstructed. Without the data, lines cannot be compared across seasons or environments; GxE analysis is impossible; the genetic progress achieved cannot be verified; the variety release process (NVRC submission) cannot proceed; and the breeding programme must effectively restart from a previous checkpoint.

References and Attributions [Series 5]

Textual References (Books and External Sources)

1. Acquaah, G. (2012). Principles of plant genetics and breeding (2nd ed.). Wiley-Blackwell.
2. Falconer, D. S., & Mackay, T. F. C. (1996). Introduction to quantitative genetics (4th ed.). Longman.
3. Chahal, G. S., & Gosal, S. S. (2002). Principles and procedures of plant breeding. Alpha Science International.
4. HarvestPlus. (2020). Biofortification progress briefs: Nigeria. CGIAR HarvestPlus Programme.
5. NAPRI. (2019). Annual report: National Animal Production Research Institute, Shika, Zaria.

Figures, Plates, Tables, and Boxes

6. Figure 5.1: Stepwise procedure for controlled hand-crossing in crop plants. Attribution: AI generated. Suggested OER search string: “plant hand crossing emasculation bagging pollination procedure flowchart diagram OER”.
7. Box 5.1: Standard record types for plant and animal breeding programmes in Nigeria. Attribution: AI generated. Suggested OER search string: “farm records plant animal breeding programme pedigree production health reproductive table OER”.