Technology options for feeding 10 billion people

Plant breeding and innovative agriculture

Annexes
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Plant breeding and innovative agriculture

Annexes
IP/A/STOA/FWC/2008-096/Lot7/C1/SC1 - SC3
October 2013
The STOA project ‘Technology options for feeding 10 billion people - Plant breeding and innovative agriculture’ was carried out by the Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe.

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**LINGUISTIC VERSION**

Original: EN

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To contact STOA please write to STOA@ep.europa.eu
This document is available on the Internet at: http://www.europarl.europa.eu/stoa/

Manuscript completed in August 2013

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CAT BA-03-13-606-EN-C
DOI 10.2861/38973
Technology options for feeding 10 billion people
Plant breeding and innovative agriculture
Annexes

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Annex B: Constraints for agricultural production in Europe
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Technology options for feeding 10 billion people

Plant breeding and innovative agriculture

Annex A: Data on global and European agriculture
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A1.1. Rice

Figure A1: Global geographical distribution of wheat and rice cultivation in 2000

Source: Beddow et al. 2010, p. 30
Figure A2: Global harvested area of rice 2011 (ha)

Source: FAOSTAT 2013
Figure A3: Global production of rice 2011 (tonnes)

Source: FAOSTAT 2013

Figure A4: Rice production selected countries and worldwide 2011 (tonnes)

Source: FAOSTAT 2013
Figure A5: Rice yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOStat 2013
Figure A6: Rice production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
Figure A7: Rice production EU-27, 2011 (1,000 t)

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Source: EUROSTAT 2013a
A1.2. Wheat

Figure A8: Global harvested area of wheat 2011 (ha)

Source: FAOSTAT 2013
Figure A9: Global production of wheat 2011 (tonnes)

![Pie chart showing global production of wheat 2011 by region.](chart1.png)

Source: FAOSTAT 2013

Figure A10: Wheat production selected countries and worldwide 2011 (tonnes)

![Pie chart showing wheat production by selected countries and worldwide.](chart2.png)

Source: FAOSTAT 2013
Figure A11: Wheat yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
Figure A12: Wheat production area EU-27, 2011 (1,000 ha)

[Diagram showing wheat production area EU-27, 2011 (1,000 ha)]

Source: EUROSTAT 2013a
Figure A13: Wheat production EU-27, 2011 (1,000 t)

Note: Malta: data not available
Source: EUROSTAT 2013a
Figure A14: Wheat yields in EU-27, average 2009-2011 (100 kg/ha)

Notes: Bulgaria average 2010-2011
       Ireland average 2009-2010

Source: EUROSTAT 2013a
A1.3. Barley

Figure A15: Barley production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
**Figure A16:** Barley production EU-27, 2011 (1,000 t)

Source: EUROSTAT 2013a
**Figure A17:** Barley yields in EU-27, average 2009-2011 (100 kg/ha)

Notes: Bulgaria average 2010-2011  
Slovenia average 2010-2011

Source: EUROSTAT 2013a
A1.4. Maize

Figure A18: Global geographical distribution of corn and soybean cultivation in 2000

Source: Beddow et al. 2010, p. 31
Figure A19: Global harvested area of maize 2011 (ha)

Source: FAOSTAT 2013
**Figure A20: Global production of maize 2011 (tonnes)**

- **Central Asia**: 1237200
- **Europe**: 106571292
- **Oceania**: 581093
- **Northern America**: 32460500
- **Southern Asia**: 31623873
- **South-Eastern Asia**: 37365029
- **Southern Africa**: 12764543
- **Sub-Saharan Africa**: 5791361
- **South America**: 91780992
- **Central America + Caribbean**: 3001448
- **Northern Africa + Western Asia**: 12764543

**Source:** FAOSTAT 2013
Figure A21: Maize production in selected countries and worldwide 2011 (tonnes)

Source: FAOSTAT 2013
Figure A22: Maize yields in global regions, average 2009-2011 (in 100 kg/ha)

Source: FAOSTAT 2013
Figure A23: Maize production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
Figure A24: Maize production EU-27, 2011 (1,000 t)

Source: EUROSTAT 2013a
Figure A25: Maize yields in EU, average 2009-2011 (100 kg/ha)

Notes: Belgium average 2009 + 2011
       Bulgaria average 2010-2011
       Denmark average 2010-2011
       Slovenia average 2010-2011

Source: EUROSTAT 2013a
A.2 OILCROPS

A2.1. Soybean

Figure A26: Global harvested area of soybean 2011 (ha)

Source: FAOSTAT 2013
**Figure A27: Global production of soybean 2011 (tonnes)**

![Pie chart showing global soybean production by region.]

- **Northern America:** 874,179,000 tonnes
- **Central America + Caribbean + South America:** 136,291,049 tonnes
- **Sub-Saharan Africa:** 176,448,5 tonnes
- **Northern Africa + Western Asia + Central Asia:** 214,579 tonnes
- **Southern Asia + South-Eastern Asia + Eastern Asia:** 15,832,099 tonnes
- **Europe:** 5,795,746 tonnes
- **Oceania:** 29,750 tonnes

**Source:** FAOSTAT 2013

**Figure A28: Soybean production in selected countries and worldwide 2011 (tonnes)**

![Pie chart showing soybean production by country.]

- **Argentina:** 48,878,800 tonnes
- **Brazil:** 74,875,400 tonnes
- **India:** 12,982,000 tonnes
- **China:** 14,885,025 tonnes
- **United States of America:** 82,171,000 tonnes
- **Rest of the World:** 27,282,966 tonnes

**Source:** FAOSTAT 2013
Figure A29: Soybean yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
Figure A30: Soybean production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
Figure A31: Soybean production EU-27, 2011 (1,000 t)

Source: EUROSTAT 2013a
Figure A32: Soybean yields in EU, average 2009-2011 (100 kg/ha)

Notes: Bulgaria average 2010-2011
Greece average 2010-2011
Lithuania only 2011
Slovenia only 2010
Source: EUROSTAT 2013a
A2.2. Rapeseed

Figure A33: Global harvested area of rapeseed 2011 (ha)

Source: FAOSTAT 2013
Figure A34: Global production of rapeseed 2011 (tonnes)

Source: FAOSTAT 2013

Figure A35: Rapeseed production of selected countries and worldwide 2011 (tonnes)

Source: FAOSTAT 2013
Figure A36: Rapeseed yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
Figure A37: Rapeseed production area EU-27, 2011 (1,000 ha)

Notes: Germany (DE) data for 2009
       Ireland (IE) data for 2009

Source: EUROSTAT 2013a
Figure A38: Rapeseed production EU-27, 2011 (1,000 t)

Notes: Germany (DE) data for 2009
Ireland (IE) data for 2009

Source: EUROSTAT 2013a
Figure A39: Rapeseed yields in EU, average 2009-2011 (100 kg/ha)

Notes:  
Belgium average 2009-2010  
Germany only 2009  
Ireland only 2009  
Slovenia average 2010-2011  
Cyprus, Greece, Malta, Portugal: data not available

Source: EUROSTAT 2013a
A2.3. Sunflower

Figure A40: Global harvested area of sunflower seed 2011 (ha)

Source: FAOSTAT 2013
Figure A41: Global production of sunflower seed 2011 (tonnes)

Source: FAOSTAT 2013

Figure A42: Sunflower seed production of selected countries and worldwide 2011 (tonnes)

Source: FAOSTAT 2013
Figure A43: Sunflower seed yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
Figure A44: Sunflower seed production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
Figure A45: Sunflower seed production EU-27, 2011 (1,000 t)

Source: EUROSTAT 2013a
Figure A46: Sunflower seed yields in EU, average 2009-2011 (100 kg/ha)

Note: Bulgaria average 2010-2011
Source: EUROSTAT 2013a
A3. PULSES

Figure A47: Global harvested area of pulses 2011 (ha)

Source: FAOSTAT 2013
Figure A48: Global production of pulses 2011 (tonnes)

Source: FAOSTAT 2013
Figure A49: Pulses yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
Figure A50: Pulses production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
Figure A51: Pulses production EU-27, 2011 (1,000 t)

![Pie chart showing pulses production EU-27, 2011 (1,000 t)]

Source: EUROSTAT 2013a
Figure A52: Pulses yields in EU, average 2009-2011 (100 kg/ha)

Notes: Bulgaria average 2010-2011
Germany average 2010-2011
Ireland only 2009
Netherlands average 2009-2010
Portugal only 2009
Slovenia average 2010-2011
Sweden average 2010-2011

Source: EUROSTAT 2013a
A4. ROOTS AND TUBERS

A4.1 Potato

Figure A53: Global harvested area of potato 2011 (ha)

Source: FAOSTAT 2013
Figure A54: Global production of potato 2011 (tonnes)

Source: FAOSTAT 2013

Figure A55: Potato production in selected countries and worldwide 2011 (tonnes)

Source: FAOSTAT 2013
Figure A56: Potato yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
Figure A57: Potato production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
Figure A58: Potato production EU-27, 2011 (1,000 t)

Source: EUROSTAT 2013a
Figure A59: Potato yields in EU, average 2009-2011 (100 kg/ha)

Notes: Belgium average 2009 + 2011
       Bulgaria average 2010-2011
       Slovenia average 2010-2011

Source: EUROSTAT 2013a
A4.2 Cassava

Figure A60: Global harvested area of cassava 2011 (ha)

Source: FAOSTAT 2013
Figure A61: Global production of cassava 2011 (tonnes)

Source: FAOSTAT 2013
Figure A62: Cassava yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
A5. SUGAR CROPS

A5.1 Sugar beet

Figure A63: Global harvested area of sugar beet 2011 (ha)

Source: FAOSTAT 2013
Figure A64: Global production of sugar beet 2011 (tonnes)

Source: FAOSTAT 2013

Figure A65: Sugar beet production in selected countries and worldwide 2011 (tonnes)

Source: FAOSTAT 2013
Figure A66: Sugar beet yields in global regions, average 2009-2011 (100 kg/ha)

Source: FAOSTAT 2013
Figure A67: Sugar beet production area EU-27, 2011 (1,000 ha)

Source: EUROSTAT 2013a
Figure A68: Sugar beet production EU-27, 2011 (1,000 t)

Source: EUROSTAT 2013a
Figure A69: Sugar beet yields in EU, average 2009-2011 (100 kg/ha)

Notes: Belgium: average 2009 + 2011
Ireland: only 2009
Bulgaria, Estonia, Cyprus, Latvia, Luxembourg, Malta, Slovenia: data not available

Source: EUROSTAT 2013a
A6. EU AGRICULTURAL LAND USE AND HOLDINGS

Figure A70: Arable land, permanent crops, permanent grassland, kitchen gardens and total land area of the EU Member States

Source: EUROSTAT 2013b
Figure A71: Distribution of utilized agricultural area (UAA) by UAA size of the farm

Source: EUROSTAT 2013c
Figure A72:  Average utilised agricultural area per holding in EU Member States, 2010

Source: EUROSTAT 2013b
### Table A1: Number of agricultural holdings in EU Member States, 1966-2010

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<tr>
<td>PT</td>
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</tr>
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<td></td>
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</tr>
<tr>
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<td>233.2</td>
<td>186.7</td>
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(1) EC/EU, aggregate calculated for the countries being Member States in the reference year.
(9) Provisional data for SE, LU, RO, UK.

Source: EUROSTAT 2012, p. 12
Table A2: Stand gross margin (SGM) of smaller and larger farms per farm and per hectare, 2007

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<td>217.0</td>
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<td>343.8</td>
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<td>137.1</td>
</tr>
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<td>CH</td>
<td>:</td>
<td>:</td>
</tr>
</tbody>
</table>

Source: Eurostat — FSS

Source: EUROSTAT 2013c
REFERENCES
   http://epp.eurostat.ec.europa.eu/portal/page/portal/agriculture/data/database
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Annex B: Constraints for agricultural production in Europe
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| Figure B3: | Natural susceptibility of European soils to compaction | 5 |
| Figure B4: | Observed drought episodes in Europe from 1971-2011 | 6 |
| Figure B5: | Percent of groundwater bodies in poor quantitative status in 2009 per river basin district | 7 |
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CONSTRAINTS FOR AGRICULTURAL PRODUCTION IN EUROPE

B1. Soil

Figure B1: Risk of soil erosion in Europe

Source: [http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/Resources/Pesera_high.jpg](http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/Resources/Pesera_high.jpg)
Figure B2: Organic carbon content of European topsoils

Source: http://eusoils.jrc.ec.europa.eu/ESDB_Archive/octop/Resources/Octop_high.jpg
Figure B3: Natural susceptibility of European soils to compaction

**B2. Water**

Figure B4: Observed drought episodes in Europe from 1971–2011

Note: A country is coloured with orange if drought episodes have occurred in that country during the reference decade, regardless of their temporal and spatial (local or nationwide) scale. No distinction between the severity, the frequency and the extent of the events is made. It is recognised that this is a simple representation based on MSs’ identification and is not based on an in-depth analysis based on harmonised criteria and indicators.

Source: Kossida et al. 2012, p. 17
Figure B5: Percent of groundwater bodies in poor quantitative status in 2009 per river basin district

Source: EEA 2012, p. 37

Figure B6: Water stress in Europe

Source: EEA 2005, p. 56
Figure B7: Current localisation of water scarce river basins in Europe all year around (on the left) and in summer (on the right) with Water Gap Modelling

Source: Strosser et al. 2012, p. 25
B3. Fertilizer

Figure B8: Mineral nitrogen fertiliser application, EU-27 in 2005

Figure B9: Manure nitrogen fertiliser application, EU-27 in 2005

Figure B10: Total nitrogen fertiliser application, EU-27 in 2005

Figure B11: Nitrogen surplus (kg N per ha), average 2001-2004 and 2005-2008, EU-27, CH and NO


(1) Data not available for 2001-2004
(2) Eurostat estimations
(3) PL, RO, BG, CZ, HU, LV, LT, EE, SI, SK
(4) Average 2002-2004
Figure B12: Mineral phosphorus fertilizer application, EU-27 in 2005

Figure B13: Manure phosphorus fertilizer application, EU-27 in 2005

Figure B14: Total phosphorus fertilizer application, EU-27 in 2005

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Annex C: EU Farming Systems
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EU FARMING SYSTEMS

In the frame of the STOA project “Feeding 10 billion people”, a simplified scheme of farming systems is needed for the qualitative assessment of agricultural production systems and technologies in the EU. Farm typologies are part of the EU agricultural statistics, in use in both Farm Accounting Data Network (FADN) and Farm Structure Survey (FSS). In the SEAMLESS project, 175 farm types were identified for quantitative analysis which linkage economic data to environmental data (Anderson et al. 2006). This approach is far too detailed for the STOA project.

Five farming systems in the EU were identified which represent the most important typical farming situations without covering all existing farm types in the EU. Livestock, horticulture and permanent crop farming systems are not included due to the scope of the STOA project. Therewith, not the whole EU agriculture with all its differentiations is mapped. Criteria for the selection of the farming systems are:

> Farm size
> Production intensity
> Specialisation
> Integration in food chains

Additionally, the identified five farming systems represent different dominant regional settings of farming in the EU. The following chapters give a short characterisation of these farming systems.

C1. Extensive small-scale, semi-subsistence farming

Semi-subsistence farmers are farmers allocating more than 50% of the output for household consumption (Chapter 2.3). Normally, they are not integrated in modern food chains. In the EU-27, they represent (Davidova 2011):

> 43.1% of all holdings,
> 38.7% of persons regular working in agriculture,
> 28.6% of regular labour (AWU),
> 7.6% of utilised agricultural area (UAA),
> 5.0% of total livestock units (LSU) and
> 3.9% of total standard gross margin (SGM).

Semi-subsistence farming is of any importance in the new Member States and in the Mediterranean countries (Tab. 1). Romania is the leading country.

Location in unfavourable areas is more typical for the smallest holdings in the EU-15 than in the new Member States, where only 31% are located in less favoured areas (LFAs) (Davidova 2011). Therewith, semi-subsistence farming is not restricted to LFAs.

Around 75% of the Greek semi-subsistence farmers belong to the farmtype specialist olives. For Italy, the picture is a little more differentiated with around 50% farmtype specialist olives, 9% farmtype specialist vineyard, 9% farmtype specialist permanent crops combined, 6% farmtype specialist fruit and citrus fruit and 3% farmtype specialist sheep, goats and other grazing livestock. In contrast, semi-subsistence farming in Romania is very heterogeneous and includes different types of cropping, livestock and mixed farming: around 17% farmtype specialist various crops and livestock, 14% farmtype specialist general field cropping, 9% farmtype specialist cereals, oilseeds and protein corps, 10% farmtype specialist poultry, 11% farmtype specialist granivores combined, 10% farmtype mixed livestock mainly grazing and 3% farmtype mixed cropping (FAOSTAT 2013a).
### Table C1: Semi-subsistence farming in EU Member States, 2007

<table>
<thead>
<tr>
<th>Member State</th>
<th>Number of semi-subsistence farms (1,000)</th>
<th>Utilised agricultural area (ha)</th>
<th>Regular labour (persons)</th>
<th>Regular labour (AWU)</th>
<th>Livestock units (LSU)</th>
<th>Standard gross margin (SGM)</th>
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Source: Davidova 2011

Semi-subsistence agriculture in Europe encompasses a heterogeneous group of holders with different motivations (Davidova 2011):

- Farmers pushed to subsistence by market imperfections and an underdeveloped social safety net for whom semi-subsistence is a coping strategy;
- Part-time farmers with other gainful activities;
- Semi-subsistence farmers by choice, sometimes known as hobby or lifestyle farmers.
Main function of most small-scale farms (< 2 ESU) in the new Member States is to provide food for the family and relatives while only surplus goes to the market. Most of these contacts are with local markets or in the form of direct sales from the farm or selling on road sides. They have practically no direct relations with modern food chains such as large retailing systems (Csaki, Forgacs 2009, p. 16).

In the face of restricted employment perspectives outside agriculture, a development of the farm structure as in EU-15 in the past with abandoning of small-scale farming becomes more unlikely and chances for improving semi-subsistence farming should be explored. With the financial and economic crisis, semi-subsistence farming could become even more widespread.

**C2. Extensive farming in less favoured areas**

In the European Union, less-favoured area (LFA) is a term used to describe an area with natural handicaps (lack of water, climate, short crop season and tendencies of depopulation or that is mountainous or hilly, as defined by its altitude and slope. Overall, they are characterised by lower land productivity.

Mountain and hill areas are most the important less favoured areas in agricultural production (Figure 1). Extensive livestock production on permanent grassland is important, with beef farm type for example in parts of Austria, France, Germany, Ireland, Estonia, Latvia and Poland, and sheep and goat farm type in the northern and western part of United Kingdom, Portugal and the southern part of Spain. But especially cereal production is also important in the less favoured areas of the EU. Arable systems characterised by a high degree of fallow dominate in parts of Spain (Kempen et al. 2011).

Based on data from the Farm Accounting Data Network (FADN), 54% of all farms are located in less-favoured areas, 16% in LFA Mountain and 38% in LFA Other than mountain areas (EC 2008). Table 2 shows the number of holdings and the agricultural area in less favoured areas by Member States as recorded in the Farm Structure Survey 2007.

Farming in less favoured areas is characterised by extensive production systems. The regional distribution of low-input farm types corresponds with location of less-favoured areas. For the EU-15 in 2000, low-input farm types were mainly concentrated in the Iberian Peninsula, on Mediterranean islands, the north and west of the United Kingdom and in central France (EEA 2005, p. 30).
Traditional land-use systems have mainly persisted in upland and remote areas where physical constrains have prevented a modernisation of agriculture (Plieninger et al. 2006). Part of the LFA is used by high nature value (HNV) farms. HNV farming systems were first defined by Baldock et al. 1993 as “predominantly low-intensity systems which often involve a relatively complex interrelationship with the natural environment. They maintain important habitats both on the cultivated or grazed area (for example, cereal steppes and semi-natural grasslands) and in features such as hedgerows, ponds and trees, which historically were integrated with the farming system. [...] The semi-natural habitats currently maintained by HNV farming are particularly important for nature conservation in the EC because of the almost total disappearance of large scale natural habitats.”

Extensive livestock systems play in important role in the less-favoured areas, but also diverse extensive cropping systems are employed. In the STOA project, the farming system “Extensive farming in less favoured areas” refers to arable farming and/or the crop production component of farms.
Figure C2: Likelihood of High Nature Value farmland presence in EU-27

Source: Paracchini et al. 2008, p. 27
## Table C2: Number of holdings and agricultural area in less favoured areas and mountain areas within less favoured areas in EU Member States, 2007

<table>
<thead>
<tr>
<th>Member State</th>
<th>Less favoured areas</th>
<th>Mountain areas within less favoured areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of holdings</td>
<td>Percentage of total holdings (%)</td>
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<td>Belgium</td>
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<td>Denmark</td>
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<td>-</td>
</tr>
<tr>
<td>Germany</td>
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</tr>
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</tr>
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</tr>
<tr>
<td>Greece</td>
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<td>60.7</td>
</tr>
<tr>
<td>Spain</td>
<td>690,080</td>
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</tr>
<tr>
<td>France</td>
<td>233,240</td>
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<td>Cyprus</td>
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<td>Malta</td>
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<tr>
<td>Netherlands</td>
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</tr>
<tr>
<td>Austria</td>
<td>118,360</td>
<td>71.6</td>
</tr>
<tr>
<td>Poland</td>
<td>1,023,190</td>
<td>42.8</td>
</tr>
</tbody>
</table>
Portugal | 200,650 | 72.9 | 3,046,450 | 87.7 | 141,730 | 51.5 | 997,290 | 28.7
Romania | 1,057,850 | 26.9 | 4,224,660 | 30.7 | 690,580 | 17.6 | 2,712,260 | 19.7
Slovenia | 58,130 | 77.2 | 356,420 | 72.9 | 42,140 | 55.9 | 258,790 | 52.9
Slovakia | 45,160 | 65.5 | 1,442,700 | 74.5 | 18,710 | 27.1 | 664,570 | 34.3
Finland | 68,230 | 100.0 | 2,292,290 | 100.0 | 39,220 | 57.5 | 1,212,130 | 52.9
Sweden | 45,770 | 63.0 | 1,482,890 | 47.6 | 13,360 | 18.4 | 343,600 | 11.0
United Kingdom | 97,540 | 32.5 | 7,443,310 | 46.1 | 0 | 0.0 | 0 | 0.0

Note: - not applicable
Source: EUROSTAT (2012)

### C3. Medium intensive, mixed farming systems

Mixed farming systems are characterised by low specialisation. They combine crop and livestock production in different patterns. In the last decades, area and number of holdings for mixed farming system decreased with the specialisation and intensification in crop production and the decoupling of crop and livestock production (Poux 2008).

For mixed farm types, Poland forms an important cluster. Also larger areas in France, Spain and Greece are dominated by those farm types. A special pattern occurs in Germany where mixed farming is scattered in smaller areas across the country (Kempen et al. 2011).

Mixed farming systems occupy over 10% of the total utilised agricultural area in Belgium, Czech Republic, Denmark, Germany, France, Latvia, Lithuania, Hungary, Poland, Portugal, Romania, Slovenia and Slovakia (Table 3).

Partly, mixed farming systems combine lower intensity arable systems with extensive livestock. Such systems can be found in interior regions of Mediterranean countries such as Portugal, Spain, Italy and Greece, and are common in many parts of eastern Poland and in Romania. The farms are mostly small scale (Cooper et al. 2009, p. 44). Extensive small-scale, semi-subsistence farms which combine crop and livestock production are not part of the mixed farming system because they are allocated to the semi-subsistence farming system (Chapter C1).

In the other areas, mixed farms show often a medium intensity in crop and livestock production. Compared to intensive specialist arable farms, field size are often smaller and more landscape elements may be present, but grazing is likely to be on intensive, temporary grassland, and livestock may be housed (Cooper et al. 2009, p. 44). In the EU-15, large scale (> 40 ESU) mixed farms with medium intensity is the second most important farm type measured by share of agriculture area. The share of this mixed farm type is 5.7% of the agricultural area, 1.7% of all farms, 5.0% of overall livestock units and 3.8% of total agricultural output in EU-15 (Andersen et al. 2006, p. 20).
### Table C3: Number of holdings and agricultural area for mixed farming in EU Member States, 2010

<table>
<thead>
<tr>
<th>Member State</th>
<th>Mixed farming</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of holdings</td>
<td>Percentage of total holdings (%)</td>
<td>Agricultural area (ha)</td>
<td>Percentage of total area (%)</td>
</tr>
<tr>
<td>Belgium</td>
<td>4,350</td>
<td>10.2</td>
<td>207,630</td>
<td>15.3</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>73,790</td>
<td>19.9</td>
<td>201,140</td>
<td>4.5</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>3,720</td>
<td>16.3</td>
<td>1,270,190</td>
<td>36.5</td>
</tr>
<tr>
<td>Denmark</td>
<td>4,500</td>
<td>10.7</td>
<td>309,210</td>
<td>11.7</td>
</tr>
<tr>
<td>Germany</td>
<td>29,420</td>
<td>9.8</td>
<td>2,988,340</td>
<td>17.9</td>
</tr>
<tr>
<td>Estonia</td>
<td>2,380</td>
<td>12.1</td>
<td>86,680</td>
<td>9.2</td>
</tr>
<tr>
<td>Ireland</td>
<td>2,450</td>
<td>1.8</td>
<td>137,620</td>
<td>2.8</td>
</tr>
<tr>
<td>Greece</td>
<td>48,320</td>
<td>6.7</td>
<td>338,330</td>
<td>9.7</td>
</tr>
<tr>
<td>Spain</td>
<td>33,170</td>
<td>3.4</td>
<td>1,323,000</td>
<td>5.6</td>
</tr>
<tr>
<td>France</td>
<td>43,520</td>
<td>8.4</td>
<td>3,321,910</td>
<td>11.9</td>
</tr>
<tr>
<td>Italy</td>
<td>35,590</td>
<td>2.2</td>
<td>545,990</td>
<td>4.2</td>
</tr>
<tr>
<td>Cyprus</td>
<td>1,940</td>
<td>5.0</td>
<td>5,500</td>
<td>4.6</td>
</tr>
<tr>
<td>Latvia</td>
<td>11,140</td>
<td>13.4</td>
<td>262,960</td>
<td>14.6</td>
</tr>
<tr>
<td>Lithuania</td>
<td>41,670</td>
<td>20.8</td>
<td>535,190</td>
<td>19.5</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>130</td>
<td>5.9</td>
<td>9,800</td>
<td>7.5</td>
</tr>
<tr>
<td>Hungary</td>
<td>78,630</td>
<td>13.6</td>
<td>789,450</td>
<td>16.8</td>
</tr>
<tr>
<td>Malta</td>
<td>310</td>
<td>2.5</td>
<td>460</td>
<td>4.0</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1,910</td>
<td>2.6</td>
<td>80,290</td>
<td>4.3</td>
</tr>
<tr>
<td>Austria</td>
<td>8,140</td>
<td>5.4</td>
<td>165,640</td>
<td>5.8</td>
</tr>
<tr>
<td>Poland</td>
<td>336,930</td>
<td>22.4</td>
<td>3,397,190</td>
<td>23.5</td>
</tr>
<tr>
<td>Portugal</td>
<td>51,280</td>
<td>16.8</td>
<td>500,280</td>
<td>13.6</td>
</tr>
<tr>
<td>Romania</td>
<td>674,970</td>
<td>17.5</td>
<td>1,586,350</td>
<td>11.9</td>
</tr>
<tr>
<td>Slovenia</td>
<td>11,420</td>
<td>15.3</td>
<td>66,380</td>
<td>13.8</td>
</tr>
<tr>
<td>Slovakia</td>
<td>5,570</td>
<td>22.8</td>
<td>524,430</td>
<td>27.7</td>
</tr>
</tbody>
</table>

---

10
### C4. Intensive, larger-scale crop farming

Cereals are the most important crop production in the EU (Chapter 2.3). The highest level of cereals production relative to the region’s area was recorded in Sjælland (Denmark) and Picardie (France), both with over 260 tonnes per km² in 2010. Cereals production in excess of 130 tonnes per km² was recorded for four out of the five Danish regions, as for four of the seven Hungarian regions and eight of the 22 French regions (Figure 3). Such an intensity of cereals production relative to land area was also recorded in several regions in Belgium, Germany, Italy, Poland and the United Kingdom (EUROSTAT 2013b).

In the EU-15, the most important farm type was 2000 large scale, medium intensity, arable/cereal with 11.6% of the agricultural area, 2.7% of all farms, 1.6% of overall livestock units and 5.9% of total agricultural output in EU-15 (Andersen et al. 2006, p. 20). In this assessment, the cereal farmtype has only medium intensity because intensity is measured by overall agricultural output so that high intensity is related to intensive livestock and horticulture farming.

Specialised cereal farms had an average size about 50 ha UAA in 2009, with no split between EU15 and EU10. Farms twice this size or more were predominant in Bulgaria, the Czech Republic, Germany, the Baltic states, Sweden, Slovakia and the United Kingdom. In terms of economic size, British cereal farms were the biggest, with about 100 ESU. German and French farms followed closely, with about 70 ESU. Also Slovak and Czech cereal farms were well above the average size of about 50 ESU per farm (EC 2013).

Farm types with a high degree of specialised crops (e.g., potato, sugar beet, cotton) dominate in parts Belgium, the Netherlands, Germany and Greece (Figure 4) and mixed arable systems dominate especially in parts of England and Italy (Kempen et al. 2011).

The regions with concentrated cereal and specialised crop production are at the same time the areas with a high degree of large-scale farms (Figure 5). Large-scale farms (> 40 ESU) dominate the north-western part of the EU (Kempen et al. 2011). Therewith, larger-scale farming is associated with low-land areas with high productivity.

Based on the IRENA report for the EU-15, high input farm types are predominant in the Netherlands, Belgium, south-eastern England, northern France, northern Italy and northern Greece (EEA 2005, p. 45). According to the IRENA fact sheet (year 2000, EU-15), an average high input farms use 126 kg N per ha per year, whereas the same figure for the average low input farm is 19 kg (Elbersen, Andersen 2008).
Figure C3: Harvested production of cereals (including rice), by NUT2 regions, 2010 (tonnes per km²)

Harvested production of cereals (including rice), by NUTS 2 regions, 2010 (*) (tonnes per km²)

Source: EUROSTAT 2013b
Figure C4: Distribution of arable farm types in agri-environmental zones in the EU dominated by arable farm types

Source: Kempen et al. 2011

Figure C5: Distribution of large scale farm types on agri-environmental zones in the EU

Source: Kempen et al. 2011
C5. Large-scale corporate farming

Large-scale corporate farming compromise production cooperatives and various types of farming companies. They are result of the transition process in Central and East Europe since 1990, a complex reform process including land privatisation/restitutions, decollectivization, creation of new private ownership based farming organisations, market and prize liberalisation, and the introduction of market conform support and incentive framework (Csaki, Forgacs 2009). Therewith, large-scale corporate farms are a phenomenon of the new Member States and East Germany. In these countries, the structure of the agricultural holdings is related to the particular ownership structure made up of large-scale corporate farms inherited from former state-owned cooperatives.

In Bulgaria, the Czech Republic, Hungary, Estonia and Slovakia, the larger farms occupying 20% of the utilised agricultural area (UAA) are all above 1,000 ha (EUROSTAT 2013c). Table 4 shows the average size of transformed cooperative farms and their share of the total agricultural area for the countries where they are most important.

Table C4: Transformed cooperative farms in selected Central and Eastern European countries

<table>
<thead>
<tr>
<th>Member State</th>
<th>Share of total agricultural area (%)</th>
<th>Average size (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulgaria</td>
<td>55</td>
<td>861</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>72</td>
<td>937</td>
</tr>
<tr>
<td>Hungary</td>
<td>41</td>
<td>312</td>
</tr>
<tr>
<td>Romania</td>
<td>45</td>
<td>274</td>
</tr>
<tr>
<td>Slovakia</td>
<td>88</td>
<td>1,185</td>
</tr>
<tr>
<td>Estonia</td>
<td>37</td>
<td>327</td>
</tr>
<tr>
<td>Latvia</td>
<td>10</td>
<td>297</td>
</tr>
<tr>
<td>Lithuania</td>
<td>11</td>
<td>483</td>
</tr>
</tbody>
</table>

Source: Ciaian et al. 2009

The large-scale corporate farms are the one side of the dual farm structure in these countries, with small-scale farms (partly semi-subsistence, see chapter C1) as the other side. The average area of the larger farms is close to 500 times the average size of all farms in countries such as Bulgaria (3,128 ha vs 6 ha), Romania (1,802 ha vs 3 ha) and Hungary (3,164 ha vs 7 ha) (EUROSTAT 2013c). Mainly in capital and land intensive regions, large-scale corporate farming remained important and gains in labour productivity came primarily from large farms shedding labour with the privatisation of the farms (Swinnen, Vranken 2010).

Large corporate farms tend to specialise in cereals and oilcrops (Ciaian et al. 2009). The larger farms are predominantly less intensive regarding livestock density (EUROSTAT 2013c).
REFERENCES


Technology options for feeding 10 billion people

Plant breeding and innovative agriculture

Annex D: Plant Breeding
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1. HISTORY OF SCIENTIFIC BASED PLANT BREEDING

It has been a long way from the beginnings of methodical plant breeding in the 19th Century to the entering of the first genetically modified plant varieties through genetic engineering. The first breeding attempts started much earlier, about 10,000 years ago by selecting those plants that showed particular favourable traits, such as pleasant taste or larger size of fruits (Cox 2009, p. 3; Acquaah 2007, p. 3; Hallauer et al. 2011). Those were then recultivated in the next generation and thereby domesticated. At that point of time inheritance on the genetic level was enigmatic and people didn’t know much about the principles of heredity. Selection was solely done by phenotype, thus the appearance of an individual plant (Cox 2009, p. 3). However, there is no evidence for controlled crosses between plant varieties, comparable to modern plant breeding prior to the 18th Century. Davies (2009) attributes the first implementation of controlled crosses to the German botanist Joseph Kohlreuter who analysed the ornamental plant *Dianthus herbatus* in his studies in the late 18th Century. Since then great progress in heredity knowledge and by this great achievements on the scientific level in plant breeding have been made, which lead to impressive results as shown in Figure D1 for the development of the yields of important crop plants in the USA.

Figure D1: Development of yields for corn, wheat and soybean in the USA

![Graph showing development of yields for corn, wheat and soybean in the USA](image)

bu/ac = bushels per acre
Source: Acquaah (2007), p. 9

Besides the improvement of agricultural technologies which surely accounted to this increase too, one can amount the contribution of plant breeding to this performance enhancing with 25–30% (Friedt, Ordon 1998). In addition to yield, the plant breeder has to incorporate many different breeding goals in his breeding programs to create new varieties (chapter 3.2.2). Those are e. g. the improvement of plant resistance against abiotic stresses like cold or drought, resistance against biotic stress factors like insects, fungal, bacterial or viral pathogens or the improvement of the product quality. Until today, there have
been great successes on these fields due to scientific based plant breeding and the development of technologies and knowledge which keeps moving forward rapidly.

The basic foundation that enabled plant breeding to reach these goals was the description of the legality of heredity by the Austrian monk Gregor Mendel in the middle of the 19th Century. His findings were the foundation for methodical plant breeding which started thenceforward. This point of time can be considered as the beginning of scientific based plant breeding. Since then different classical breeding methods have been developed which mainly base on his three laws. The knowledge about the biological background of inheritance has greatly increased and biotechnological tools in plant breeding have consistently been developed and improved (Reeves, Cassaday 2002).

While conventional breeding work in the past, where plants could only be evaluated by their phenotype, took mainly place in the field and transferring a favorable trait to a new variety took about 10-15 years (Jauhar 2006), plant breeders nowadays have numerous modern tools and technologies to accelerate the process of transferring specific genes of interest and identifying potential candidates on the genetic level to create new varieties, thereby using modern laboratory methods, statistical models and sophisticated bioinformatics. The invention of modern biotechnology has speeded up the regular breeding process immensely (Hock et al. 2003).

2. OVERVIEW BREEDING TECHNOLOGIES AND GOALS

2.1. Definitions of plant breeding

There is no general definition of the term “plant breeding”. Different approaches describe the main aims of plant breeding as a science and practical handcraft as well. Acquaah (2007, p. 3) sees plant breeding as “a deliberate effort by humans to nudge nature, with respect to the heredity of plants, to an advantage. The changes made in plants are permanent and heritable”. According to Friedt and Ordon (1998) plant breeding follows the aim to create varieties which deliver high and stable yields under changing environmental conditions, thereby applying genetic principals. In Schlegel’s “Dictionary of Plant Breeding” (2010, p. 274) plant breeding is defined as “the application of genetic principles and practices to development of individuals or cultivars more suited to the needs of humans; it uses knowledge from agronomy, botany, genetics, cytogenetics, molecular genetics, physiology, pathology, entomology, biochemistry, or statistics”. According to Cleveland (2001) plant breeding is furthermore not just an objective truth but represents also a “social construction” and thereby also has to be seen from a social point of view regarding social acceptation and demands.

2.2. General breeding goals

At first view, the plant breeder is confronted with a multiplicity of sophisticated breeding goals he has to pay respect while creating new varieties. A wheat breeder for example has to take account of grain development and size, cold hardiness, stableness, protein content, baking quality and also resistances against diverse pathogens, such as fungi or insects. However, by taking a closer look one can summarize all requirements of a variety with the terms “yield” and “quality”. Plant breeding nowadays does not only try to increase the yield of a variety, but especially to provide a high and stable yield in combination with a high quality of the product. As there is a drastic reduction of the potential yield of many crop plants due to pests and pathogens, plant breeding for resistance is of utmost importance too. Summarized there are three major breeding goals in plant breeding (Becker 1993):

> Yield potential
> Yield safeguarding
> Quality
As most of the traits that influence these breeding goals are inherited polygenic and/or have strong interactions with the environment, the plant breeder is continuously challenged by improving them.

2.3 Basis for inheritance

One has to keep in mind how traits of plants are influenced and on what their expression is based to understand the general breeding procedure. All traits are encoded by genes. Genes are particular DNA-sequences composed of the four DNA basic modules adenine, thymine, guanine and cytosine. The special sequence of these components encodes the expression of the trait. The characteristic of a particular trait is generally not only affected by its encoding gene or genes, but also by environmental influences.

In this context one has to differentiate between monogenic and polygenic inherited traits. Classical monogenic inherited traits such as the color of the flower or resistance towards a particular pathogen are encoded by one single gene that mainly affects the occurrence of the trait. These monogenic inherited traits are normally rarely affected by environmental influences and are thereby easy to select. This means that if a monogenic inherited trait is expressed in a favorable form in a plant, the breeder can almost be sure that the individual plant also carries the appropriate gene. He can therefore select it for further use in the breeding program.

But most of the agronomic favorable traits, such as yield or abiotic resistances are not only encoded by a single gene (inherited monogenic), but depend on the influences of several different genes that strongly interact with themselves as well as with the environment. This sort of inheritance is called “polygenic” and has challenged the plant breeders since the beginning of methodical scientific based plant breeding. The difficulty with breeding for polygenic traits is that the breeder has not only to look for single genes and incorporate them into new varieties, but he has to create varieties carrying a combination of many different genes of interest to ensure an improved performance of a new cultivar. Furthermore the genes and gene-products strongly interact among each other and with the environment as well. Therewith, typical polygenic traits like yield can extremely vary under changing environmental conditions, such as temperature. The chief attraction for the breeder is to create a variety that shows a stable performance in difference environments, delivering high and stable products of high quality.

2.4 Major steps in plant breeding

In general, every plant breeding approach follows three major steps (Wyss et al. 2001; FAO 2011, p. 6 and 7):

> Creation of a new initial genetic variation;
> Selection of suitable crossing parents for creating new varieties;
> Testing, maintenance and reproduction of a variety.

The first major step in breeding is to create a broad genetic variation where genes are recombined and are present in different compositions in individual plants. This represents the basis from which the selection of potential candidates for new varieties takes place (Friedt, Ordon 1998). There are different ways to generate genetic variation. The classical approach is to arrange simple crossings between suitable parental lines (Borlaug 1984). E.g. these can either be two high performance varieties which carry favorable traits respectively that one wants to combine or these can also be an established variety and a wild-type cultivar that carries interesting resistance traits one wants to use for creating high performance lines with resistances against particular pathogens (Friedt, Ordon 1998; Becker 1996, pp. 75-92). Modern biotechnological proceedings made it even possible to cross plant species that are naturally not or rarely combinable due to biological incompatibility mechanisms (Hallauer 2011).

Furthermore, artificial transmissions of single genes are nowadays as well possible as precise induced mutations or switch-offs of particular genes leading to modification or absence of specific gene products.
Either way it is very important to maintain genetic resources with a broad variation for each plant species to ensure a large genetic pool for combining and selecting traits. Today there are institutions called “gene banks” that only deal with storing and reproducing seeds of many different cultivars for most of the agronomic important crop plants to maintain genetic variation for all species. Worldwide around 1,300 gene banks that conserve over 6.1 million accessions are registered (Haussmann, Parzies 2009; p. 109).

In the second step the breeder then tries to identify individuals that carry the wanted traits or combinations of traits in order to select and re-use them for the next steps in his breeding program. While in the past the breeder could only include phenotypic detectable, easily measurable external and internal traits such as plant habitus, yield or measurable susceptibility or resistance against different pathogens or diseases in his validation for selection, he has now the opportunity to select plants based on genetic information and data. The breakthrough in this context was the advent of molecular markers in the 1970s and the development of marker assisted selection (MAS) (Brumlop, Finckh 2011). The main idea behind MAS was to associate particular DNA-patterns to important traits in plants and thereby select plants on the basis of their genetic composition and or of the shape of a particular molecular marker respectively. This enables targeted selection already in the youth stages of the plants and thereby shortened the breeding programs drastically (Collard et al. 2005).

The third main step in breeding new varieties mainly deals with testing, maintenance and reproduction of a new variety. Before a new cultivar can be launched, it first has to be tested in perennial and multi-spatial trials. Thereby several requirements have to be fulfilled, such as the innovation and newness of a new variety, its purity and homogeneity and its reproducibility. These factors are tested by independent institutions which can finally permit or decline the market entry of a new variety (Wyss et al. 2001).

All in all, the whole breeding procedure for developing new varieties is a very cost and time consuming process in which increased knowledge about the biological backgrounds of inheritance and the consistent improvement of biotechnologies and techniques could make great contributions.

### 3. PLANT BREEDING TECHNOLOGIES

#### 3.1. Overall breeding strategies and conventional breeding

Different plant species have different types of propagation so that the plant breeder has to apply different breeding strategies which finally result in four different major types of varieties, shown in table D1 (Borlaug 1983).

**Table D1: Propagation systems, Types of reproduction and types of varieties**

<table>
<thead>
<tr>
<th>Natural type of propagation</th>
<th>Process of reproduction</th>
<th>Type of variety</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>asexual propagation</strong></td>
<td><strong>vegetative propagation</strong></td>
<td><strong>clonal variety</strong></td>
</tr>
<tr>
<td><strong>autogamy</strong></td>
<td><strong>self-fertilization</strong></td>
<td><strong>line variety</strong></td>
</tr>
<tr>
<td></td>
<td><strong>controlled crossing of heritage components</strong></td>
<td><strong>hybrid variety</strong></td>
</tr>
<tr>
<td><strong>allogamy</strong></td>
<td><strong>open pollination</strong></td>
<td><strong>open-pollinated variety</strong></td>
</tr>
</tbody>
</table>

Source: Becker 1993, p. 191
**Clone breeding**

Plant species such as strawberries, sugarcane or potatoes are classical representatives for vegetative propagation which means that besides sexual reproduction they are able to reproduce themselves vegetatively, thus asexual. After sexual crossing of two suitable parental lines to create a genetic variation, the plant breeder selects candidates and propagates the progeny vegetatively based on plant parts and by this creates clones that are genetically equal with their ancestor.

**Breeding self-pollinated species**

Line varieties are typically generated by pure-line breeding methods using self-fertilization. Typical self-fertilizing crop plants are rice, wheat or barley. Furthermore there are crop plants like maize or rapeseed that are facultative self-fertilizing and thereby can also be bred with line breeding methods.

Like in every breeding approach, the breeding process starts with creating a new initial variation which is normally done by crossing two appropriate homozygous parental lines. According to the first Mendellian law, the resulting F1-population is uniform which makes a selection impossible in the first generation after crossing (Friedt, Ordon 1998). From the F2-population on, it is possible to choose between two distinct breeding methodologies, namely the “bulk-population method” in which the breeder starts the selection procedure in the F5 - F6 generation when there is a sufficient amount of homozygous genotypes or the “pedigree method”, in which the breeder starts selecting favorable genotypes already in the F2 generation. As there has been a continuous progress of the breeding methods different gradations of these general methodologies have been development. For a more detailed description there are numerous books and reviews about breeding methods (Becker 1993; Friedt, Ordon, 1998; Schlegel 2010; Acquaah 2007, chapter 16).

**Breeding cross-pollinated species**

In contrast to line breeding methods for breeding self-fertilizing species where the final product is a homozygous line, cross-pollinating species are bred by methods resulting in an improved heterozygous, heterogeneous population (Friedt, Ordon p. 29). Important cross-pollinating crop plants are cotton, rapeseed, rye, sunflower or fodder beet.

Like in line breeding, there are also different methods for breeding cross-pollinated species. The most common and simple one is the mass selection method (Acquaah 2007, p. 287; Friedt, Ordon 1998, p. 29). In this method the breeder selects favorable plants from a population derived from an initial crossing, mixes their seeds and sows them in the next population. A repetition of this procedure allows a defined improvement of the population. The most important factor affecting the success of selection is whether the trait of interest can be selected before or after flowering of the plants. If the trait is expressed before flowering and can therefore be selected in earlier stages, unwanted genotypes are isolated from the population. As all plants are fading together in the population (“open-pollination”) and the pollen cloud contains the gametes of the wanted and unwanted genotypes those plants expressing the trait in an undesired trait could be easily excluded from propagation to the next generation. If the trait of interest cannot be obtained until flowering, the unwanted genotypes would be propagated in the next generation and the success of selection is hindered (Friedt, Ordon 1998, p. 29). In the progress of breeding methods for cross-pollinated species, different variants based on mass selection have been developed (Friedt, Ordon 1998, p. 29-31; Becker 1993, p. 236-245; Rattunde et al. 2009, pp. 262-265).

One of the most important and established methods for breeding cross-pollinated species is the hybrid breeding method which is explained more detailed below.

**Hybrid breeding**

The foundation of the hybrid breeding method – which also represents a cross-breeding technique – was accomplished by the discovery of the “heterosis effect” in the early 20th century (Hallauer 2011) and represents a cornerstone in plant breeding history (Chan 2010). Schlegel (2010, p. 186) describes heterosis...
as “the increased vigor of growth, survival, and fertility of hybrids, as composed with the two homozygotes” that represent the parental lines of a hybrid population.

This means that the crossing of two homozygous, genetically different inbred lines results in a F1-population that shows a significant better performance than its parents. The heterosis effect causing a distinct superiority of the F1 population in comparison to its parental lines gets lost in the F2-population, when the F1-population is recultivated in the next generation. This is an important point in hybrid breeding and traces back to the second Mendelian law (Kutka 2011). This means that a farmer cannot use the produced seeds from a hybrid variety for tilling his fields in the next year, because the plants would show extreme decline in the performance of the particular traits, mostly yield. To produce a hybrid variety with the highest possible heterosis effect it is extremely important to guarantee that the mother line is solely pollinated by the father line. For that reason plant breeders nowadays use CMS (“cytoplasmatic male sterility”) lines that are unable to produce pollen and thereby serve as the mother line (Acquaah 2007, p. 71). The first hybrid cultivars were maize hybrids and came up in 1917. From the advent of the first commercial maize hybrids in the 1930s the maize yields exploded as one can see in figure D2.

Figure D2: Maize grain yields in the USA from 1866 – 1996

bu/ac = bushels per acre; Double-Cross and Single-Cross are hybrid-breeding methods
Source: Crosbie et al. (2006)

Nowadays, nearly all maize cultivars growing in major production areas are hybrids. During the development of plant breeding techniques the hybrid breeding method has become more and more important also for other crop plants. Nowadays, hybrids dominate the production areas for example for maize, rapeseed or soybean worldwide (Hallauer 2011).
3.2. Tissue culture techniques

Plant tissue culturing generally describes the approach to cultivate single plants, tissues or organs in special culture medium in order to generate either certain plant organs or whole plants on special culture media in vitro (ISAAA 2010). The background for this technique is the cell theory from Schleiden and Swan from the years 1838/39 which postulated that every single cell is autonomous and totipotent and thereby able to build up every single plant organ or an entire plant under the right environmental conditions (Friedt, Ordon 1998). The term “right environmental conditions” means in this case a sufficient amount of vital plant micro- and macro-nutrients such as nitrogen, phosphor or potassium and an adequate content of plant hormones in the culture medium. The plant hormones stimulate cell division and the formation of specific plant tissue or organs, such as plant leaves or roots (Lusser et al. 2012). These conditions have to be carefully controlled to ensure the success of the method. In the final stages one can generate a whole plant out of single cells in culture medium in vitro and then move the sedling to the soil. The regenerated plants are genetically identical with the donor plants of the cell material.

By using this technique, one can easily produce numerous disease free clones of one certain genotype. Tissue culturing has been used for breeding, propagation and improvement of different important crop plants since the 1940s (Suslow et al. 2002). There are some difficulties with this technique that have to be noted. First of all, one has to choose appropriate plant material for cultivation. For example, old plant cells are often not feasible for tissue culturing. Furthermore, it is very important that the plant material is intact and not diseased by pathogens such as bacteria, viruses or fungal spores. Once infected plant cells are cultivated on cultivation medium, the pathogens also start to propagate and reproduce but in a much faster and high frequented way than the plant cells. This leads to an immense pathogen infestation in the culture medium and finally to plant cell death. Additionally, one has to ensure to work under sterile conditions to avoid any kind of contamination of the plant material (Dagla 2012). Keeping these conditions, plant tissue culturing can be widely applied for nearly any crop plant and is also a feasible method for many developing countries for crop improvement (Suslow et al. 2002).

Embryo rescue method

The embryo rescue method is a plant tissue culture method which is used to cross plants that are genetically widely different and thereby naturally rarely or not combinable (Schlegel 2010 p. 136). This can be the case when crossing a high performance variety and a relative wild type cultivar that carries for example an interesting resistance trait. The generated hybrids from wide crosses are either not able to produce mature viable seeds (Suslow et al. 2002) or there are incompatibility mechanisms that inhibit the correct development and growth of an intact embryo (Friedt, Ordon 1998). In the latter case after fertilisation, the embryo can be isolated from the rest of the seed and cultivated on special culture medium to overcome the natural crossing barriers. Under proper conditions a hybrid plant can be generated out of this isolated embryo in vitro.

This method is well established and represents a powerful tool to enhance genetic variation in plants and to combine agronomical important traits. There are many examples where interspecific crosses by the use of the embryo rescue technique could improve agronomical important crop plants. For example, resistance traits against a fungal pathogen have successfully been transferred from topinambur into sunflower by using the embryo rescue technique. Another example is the transfer of resistance against nematodes from oil radish into oilseed rape, or the creation of the cereal crop triticale which represents a crossing between wheat and rye and plays an important role for animal feeding nowadays (Friedt, Ordon 1998).

Protoplast fusion

As described above, the embryo rescue method is a tool for overcoming crossing barriers that affect the development of hybrids generated by crosses of genetically distant related plants at the post-fertilisation
level (Mehetre, Aher 2004). But a sexual crossing is initially possible in this case. However, there are plants that can not be sexually crossed due to other crossing barriers that inhibit fertilisation (Friedt, Ordon 1998). The protoplast fusion technique has been developed to overcome these mechanisms (Haussmann, Parzies 2009, p. 109). Protoplasts are cells that have been treated with cellulose digesting enzymes and for that reason have no cell walls. The cells for protoplast creation can be taken from nearly anywhere of the plant. With chemical and enzymatic treatment these cells are isolated, lose their cell walls and finally stimulated to fuse in special medium. By fusion of two protoplasts the genetic material of the distant related plants is combined and by cultivation the fused protoplasts on culturing medium a somatic hybrid plant can be generated in vitro (Schlegel 2010, p. 289). Although the literature describes the method as relatively complicated, it theoretically provides the opportunity to do crosses between any plants species and genius and thereby enhancing genetic variation for selection (Dagla 2012; Friedt, Ordon 1998). Many recent studies on protoplast fusions for many different crop plants prove the current importance of the technique for plant breeding.

**Haploids and doubled haploids in plant breeding**

Normally, every fertile plant carries a doubled set of chromosomes (2n) consisting of one chromosomal set from each parent respectively. This constitution is described by the term “diploid”. The diploid set of genetic material is then recombined and bisected during gamete production in meiosis leading to “haploid” egg or sperm cells that carry only one chromosomal set (1n). Meiosis is a very vital process with two major aspects: On the one hand recombination of chromosomes and chromosome parts during chromosome pairing in meiosis keeps up genetic variation; on the other hand bisection of the diploid chromosome sets secures diploidy in the offspring when it comes to combination of the haploid sperm and egg cells by crossing two genotypes.

Although they are not directly feasible for classical breeding processes, one can generate whole haploid plants out of haploid cells. As a matter of fact haploid plants provide interesting opportunities for plant breeding. They fail a correct process of meiosis leading to sterility and the inability to propagate sexually due to their single set of chromosomes (1n). By using the natural toxic colchicine, derived from plants of the genus *Colchicum*, the sterility can be reversed as colchicine treatment of plants leads to chromosome doubling and thereby restores diploidy (2n) and fertility. Diploid plants that have been created with colchicine treatment out of haploids are called “doubled haploids” (DHs). Discussions about harnessing haploids and DHs for crop improvement and research on this field already started in the early 1970s (Germanà 2011) and finally led to wide usage of haploids and DHs in practical plant breeding nowadays.

In DHs the doubled chromosome sets are completely identical which leads to entire genetic homogeneity of the plants. This is greatly desired in plant breeding for different reasons. Before the application areas of DHs are discussed at first the generation of haploid and doubled haploid plants shall be briefly described.

Principally there are different techniques to produce haploid and doubled haploid plants. Due to their superior importance for practical plant breeding, this report will only focus on methods based on androgenesis, also called “pollen embryogenesis”. These synthesis pathways are initiated from male gametes (Germanà 2011). The two important androgenesis techniques for haploid- and DH-production are microspore and anther culturing (Seguí-Simarro, Nuez 2008a).

In microspore culturing, the spores are isolated from the anthers of the flowers and then cultivated on culture medium. It is important to keep in mind that these microspores represent the male gametes of a plant, comparable with sperm cells, which only carry a haploid set of chromosomes (1n). Special compositions of plant hormones in the medium induce the formation of an embryo and finally a whole, haploid plantlet (Seguí-Simarro, Nuez 2008b). In anther culturing, the whole anthers which carry the plants microspores are cultivated on special medium whose hormone-constitution first of all induces callus formation. Based on the callus an embryo is then generated which finally leads to the formation of
a haploid plantlet (Maraschin et al. 2005). Afterwards, the whole generated haploid plantlet is treated with the natural toxic colchicine. This leads to chromosome doubling at the cell division stage in mitosis of the growing plantlet resulting in a DH plant (Forster et al. 2007).

The chromosome doubling of haploid plants results in the formation of DHs which are entirely homozygous. This means that all alleles for every single gene have the same characteristic. A maximum level of homogeneity is extremely important, especially in pure-line and hybrid breeding (Crosbie 2006).

As there is a bisection of the content of heterozygous genotypes in autogamic propagated plant populations in every generation, it takes 6-7 cycles of self-propagation ($F_6$-$F_7$ = filial generation 6-7) until a sufficient level of homogeneity in the population is reached and the breeder can start performance testings with variety candidates (Friedt, Ordon 1998). It formerly took at least six to seven years of self-propagation in breeding line varieties from the initial crossing of two genotypes in the beginning of the breeding process until the breeder could start to analyze the performances of the candidate-cultivars seriously. The invention of the DH-method shortens this progress drastically. After crossing the parents in the beginning one can generate DH-plants out of the $F_1$-population using androgenesis based methods. This results in a completely homozygous $F_2$-DH-population which is then feasible for selection. The period of time from the generation of a genetic variation until the achievement of homogeneity is thereby extremely shorted compared to classical methods.

**Micropropagation**

Micropropagation is a tissue culture technique to produce great numbers of uniform, disease free plants of high quality (Suslow et al 2002; Lusser et al. 2012; ISAAA 2010). Thereby, one follows the general tissue culturing steps using plant material of the meristem which consists of young and actively dividing cells (Suslow et al. 2002; ISAAA 2010; Schlegel 2010 p. 34 and 169). These cells can be cultivated in suitable culturing medium (as described above) to produce numerous disease-free copies of one single plant. This is because the meristem, from where the cells are taken, is generally not infested by viruses (Dagla 2012). This is a big improvement in breeding plants that are propagated asexually such as potatoes or strawberries (Suslow et al. 2002). The classical way of propagating e. g. potatoes is to plant the buds, or “eyes”. By this technique viruses which are present in the donor-plant are transmitted to the new crops every year. Micropropagation avoids this problem. The method has been applied in strawberry breeding since the early 1980s and nowadays many ornamental plants such as orchids and gerbera are exclusively propagated by micropropagation (Suslow et al. 2002).

Although it is theoretically possible to create an unlimited number of identical plants from one superior plant, the method is in this context limited to somaclonal variation (Suslow et al. 2002). In the beginning of cultivating meristematic cells, it comes first to the formation of a callus, an accumulation of undifferentiated cells. However, a small fraction of these cells are genetically different from the others. This genetical differentiation happens by chance (Friedt, Ordon 1998) and is unwanted when uniform plants shall be produced. However, this phenomenon otherwise increases genetic variation that can be interesting for breeding. For example there could be found cultivates in sugar cane that showed pathogen-resistance which was derived from somaclonal variation formed in plant cell culturing.

### 3.3 Mutation breeding

Novak and Brunner (1992) consider mutations as “the fundamental source of heritable variation”. Thereby, mutations deliver genetic variation and can result in changes in the genome that may have effects on the expression of agronomical traits. As mutations occur infrequently and changes in genes are rarely (Novak, Brunner 1992; Lönning 2005), plant breeders have invented the method of mutation breeding in which they induce mutations in the genome of plants with special treatments to accelerate the process of spontaneous mutation in order to create new genetic variation (Lönning 2005). The possibility to induce mutations was discovered in the early 20th century. Interestingly, mutation breeding is paramountly applied in developing countries more than anywhere else (Lidder, Sonnino 2011).
There are different types of mutations that can occur. Pathirana (2011) divides them into ‘intragenic mutations’ (cf. point mutations) that occur within a gene, ‘intergenic mutations’ (cf. structural mutations) which lead to inversions, translocations, duplications or deletions of particular parts within chromosomes (Friedt, Ordon 1998), and mutations that lead to changes in the chromosome number. Most of the induced mutations within a mutation breeding program lead to a loss of function of affected gene (Koornneef 2002).

Factors causing mutations are called “mutagens”. Commonly the material to be treated with mutagens is seed (McCallum et al. 2000). The two major types of available agents for mutagenesis are physical and chemical mutagens (Pathirana 2011). Gamma-, X-ray and neutron radiation are the most frequently used physical mutagens used for mutation breeding (Novak, Brunner 1992). Radiation treatment of plants generally results in high frequented deletions in the DNA sequence and thereby causes drastic changes in the genome (Koornneef 2002). In contrast to physical mutagens, a treatment with chemical mutagens represents a more sensitive methodology and mostly leads to substitutions of nucleotides within the DNA sequence. The most used chemical mutagen to induce mutations is Ethyl methanesulfonate (EMS) because it is relatively easy to apply and furthermore can be detoxificated unproblematicly through hydrolysis for disposal (Pathirana 2011).

In the beginnings, mutation breeding could not measure up to the breeders’ expectations and it took about 40 years to establish profitable methods and to make mutation breeding feasible for crop improvement (Lönnig 2005). The development of high-throughput screening methods for detection of mutations made mutagenesis applicable for practical breeding approaches and resulted in new cultivars with improved characteristics (Ritchie, Nielsen 2006). The improvement of molecular techniques and tools in the last decade made it even possible to screen mutants on the gene level and thereby give information about the exact position of induced mutations in the genome. However, direct sequencing of genomic parts of interest for scanning mutations is, at this point of time, costly and time consuming and for this reason rarely used in practical mutation breeding approaches (Pathirana 2011).

During development and improvement of screening methods, “Targeting Induced Local Lesions IN Genomes” (TILLING) has emerged as a stable and reliable method for mutagenesis and detecting mutations in genes of interest by testing populations in a high-throughput manner (McCallum 2000). In this approach, TILLING populations are generated by inducing mutations with chemical mutagens. In the next step an enzymatic detection method combined with gel electrophoresis reveals single-base mismatches in the sequence highlighting the presence of a mutation in the particular gene. TILLING is nowadays applied in crop science and also practical plant breeding programmes of big companies as well (McCallum 2000; Ritchie, Nielsen 2006; Pathirana 2011; Henikoff et al. 2004).

3.4 Marker assisted breeding

In the beginnings of plant breeding in the late 19th century, selection in breeding programs relied on phenotypic information, giving the breeder information for further usage in the breeding processes (Ruane, Sonnino 2011, p. 5). Depending on the type of trait and depending on how strongly a trait is affected by environmental influences, selection based on phenotypic data limits the breeding success.

With development and improvement in plant breeding methodology, plant breeders have gained more and more information about the genetic background of agronomical important traits and the genetic composition of crop plants. Although phenotypic data is still an important base for selection, especially for qualitative traits that mainly depend on particular genes and are less affected by environmental factors, breeders and researchers nowadays make use of genetic information for selection to a big extent (Xu, Crouch 2008).

The innovation of molecular markers in the late 1970s represents a cornerstone for genetic based breeding (Brumlock, Finckh 2011), turning phenotype-based selection into a genotype-based method (Ruane, Sonnino 2011, p. 8). In the meantime, numerous molecular markers have been developed and
mapped throughout whole genomes of different agronomical important crop plants (Lusser et al. 2012). Although marker-assisted breeding always lacked behind expectations, especially for practical breeding applicability due to generally high costs and laborious methods, it is assumed to play an important role in plant breeding in the short term as well as in the long term. As marker-assisted selection (MAS) comprises diverse problems especially for polygenic traits, it is from current point of view mainly feasible for selecting monogenic or oligogenic inherited traits (Xu, Crouch 2008). The combination of phenotypic data through valuation of trait expression and genetic data through marker analysis in statistical approaches resulted in discoveries of genome-regions that show high influences on trait expressions. Those loci in genomes affecting the characteristic of a trait are called ”Quantitative trait loci (QTL)” and are based on specific statistical calculations.

**What are molecular markers?**

Molecular markers are regions in genomes whose approximate positions along the chromosomes are defined. They play an important role in plant breeding by exposing genetic differences between different genotypes on the DNA sequence level, highlighting polymorphisms of DNA fragments. Polymorphisms of molecular markers between diverse genotypes can rely on a single base-pair difference between the same DNA regions of two different genotypes. Thereby a molecular marker generally does not represent a gene or a genomic locus that affects the expression of a trait and therefore can be taken as “neutral” (Jones et al. 1997). In fact it rather marks a position in the genome that is derived from statistical calculations in a crossing population. By incorporating different markers with different positions in the genome one can construct a genetic map which will be described later in this report.

Generally, there are three different major types of markers (Winter, Kahl 1995; Jones et al. 1997):

- Morphological markers which represent traits themselves
- Biochemical markers which include isoenzymes
- DNA (or molecular) markers

Although there are some limitations for their application, morphological and biochemical markers contributed to big successes in crop improvement in the past (Collard et al. 2005).

As molecular markers (DNA markers) are the most widely used markers in plant breeding, this report will only focus on their usage and application in breeding programs.

There are different advantages that led to a wide usage of molecular markers in genomic selection in plant breeding nowadays. First, molecular markers are, contrary to phenotypic markers, less or not affected by environmental conditions. In addition, they theoretically allow much more detailed prediction of the inheritance performance of a genotype by analysing its genome, even in the very early development stages of a plant in which phenotypic validation of traits like flowering time or yield is not possible. The usage of molecular markers for marker-assisted selection (MAS) led to remarkable shortenings in the selection processes with a higher accuracy at the same time. Nowadays, numerous molecular markers distributed all over genomes have been developed.

**Types of molecular markers**

Today there are numerous different types of molecular markers which are used in practical breeding as well as in scientific approaches. Collard and Mackill (2008) name five major considerations for the use of molecular markers in marker-assisted selection, namely ‘reliability’, ‘quantity’ of DNA required, ‘technical manageability of markers’, ‘level of polymorphism’ and ‘cost’. Table D2 summarises the DNA markers that are most frequently used in scientific and practical breeding approaches.
### Table D2: Important molecular markers for marker-assisted selection (MAS)

<table>
<thead>
<tr>
<th>Molecular marker</th>
<th>Marker development principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Restriction fragment length polymorphism (RFLP) | • DNA digestion with restriction enzymes  
• Gel electrophoreses and DNA staining | • Robust  
• Reliable  
• Transferable across populations | • Laborious, expensive, time-consuming  
• Large amounts of DNA required  
• Polymorphism in related lines are limited |
| Random amplified polymorphic DNA (RAPD) | • PCR reaction with short random primers  
• Amplification of random fragments of unknown sequence  
• Gel electrophoreses and DNA staining | • Quick and simple  
• Inexpensive  
• Possible detection of multiple loci with one primer  
• Small amounts of DNA required | • Generally not transferable to other populations  
• Difficult to reproduce |
| Amplified fragment length polymorphism (AFLP) | • DNA digestion with restriction enzymes  
• Adapter ligation  
• Two circles of selective PCR reaction  
• Gel electrophoreses and DNA staining | • Multiple loci  
• High levels of polymorphism generated | • Large amounts of DNA required  
• Complicated methodology |
| Microsatellite or “Short simple repeat (SSR)” | • Consist of tandem repeats of short (1-5 bp) DNA sequences  
• PCR reaction with primers designed from DNA sequence information  
• Gel electrophoreses and DNA staining | • Once developed a technically simple procedure  
• Robust and reliable  
• Transferable across populations | • Primer development is laborious and time-consuming  
• Analysis requires laborious polyacrylamide electrophoresis |
| Single nucleotide polymorphism (SNP) | • Variations of single nucleotides between sequences, resulting from point mutations  
• DNA sequence information required for SNP detection  
• Genotype testing for particular SNPs e. g. with DNA chips | • Robust and reliable, very accurate and sensitive  
• Transferable across populations  
• Once developed, low costs per analysing run | • High costs for DNA chip development  
• Sequence data required |

Source: Collard et al. (2005); Mohan et al. (1997); Edwards, Crouch (2007); Korzun (2002); Bardakci (2001); Kumar, Gurusubramanian (2011); Maheswaran (2004); Lidder, Sonnino (2011)

Restriction fragment length polymorphism (RFLP) markers were developed in the 1970s and represent the first molecular markers used in human genome mapping (Mohan et al. 1997; Edwards, McCrough 2007). They were later also widely used in plant genome mapping. To create an RFLP-marker the genomic DNA has to be digested by specific DNA cutting enzymes called restriction enzymes which results in DNA fragments of different amounts and sizes that are mainly affected on the DNA composition of the particular genotype. By separating the fragments on a specific gel using gel-electrophoresis methods and staining them with special DNA binding dyes, a characteristic “band pattern” comparable to a barcode can be generated which allows a clear differentiation between the tested genotypes (Korzun 2002; Collard et al. 2005).

Random amplified polymorphic DNA (RAPD) markers came up in the early 1990s and were invented by Williams et al. (1990). At that point in time the most frequently used molecular markers were RFLP markers. The principle of the RAPD method is to amplify random DNA amplicons of unknown sequence by using short DNA-primers of around 10 bp length in PCR reaction that randomly bind in the genome at complementary binding site. Only those regions are amplified that are flanked by two bound
primers (Bardakci 2001). This brings different numbers of amplicons of variable sizes for each tested genotype after PCR reaction. The different amplicons can be separated and visualized in gel electrophoresis, resulting in a characteristic “band pattern” for each genotype (Kumar, Gurusubramanian 2011).

The amplified fragment length polymorphism (AFLP) marker technique was first described by Vos et al. (1995) as a tool for “genetic fingerprinting”. For AFLP marker generation, the genomic DNA has to be cut by specific restriction enzymes in a first step. In the second step, specific double stranded DNA adapters are ligated to the cut genomic DNA fragments. After ligation two “selective PCR reactions” are performed with specific primers that are derived from the adapter sequences and carry extensions that range into the restriction fragment sequences and thereby ensure selective amplification of only those fragments, in which the restriction site flanking sequences match the extensions of the specific primers. This results in a specific number of DNA fragments of various sizes that again can be visualized on gel using DNA staining dyes. The band pattern which is created is likewise highly specific for each tested genotype (Vos et al. 1995).

Microsatellite-markers, also known as “Short Simple Repeat (SSR)” markers are regions in the DNA sequence that consist of tandem repeats of short nucleotide motifs that are 1-6 bases long (Queller et al. 1993; Jarne, Lagoda 1995; Maheswaran 2004). For example a microsatellite locus might be the sequence “AT” that is repeated in one genotype for 19 times ([AT]19) and only for 17 times in another one ([AT]17). This difference can again be visualized using gel electrophoresis. SSR markers are very numerous in eukaryotes (Queller et al. 1993) and reveal sequence polymorphisms between different genotypes very reliably (Jarne, Lagoda 1995). Nowadays, they are widely applied in marker-assisted plant genotyping (Maheswaran 2004; FAO 2011a, p. 19).

Single nucleotide polymorphism (SNP) markers are variations of single nucleotides within a DNA sequence that occur within a rate of approximately one in every 1,300 base pairs in most organisms (Schlegel 2010, p. 329). SNPs result from point mutations and can be detected with different analysis methods. However, for usage of SNP markers detailed sequence information is necessary (Maheswaran 2004). The steady progress in DNA sequencing techniques, supplying extensive sequence information for nearly all important crop plants and the improvement of SNP marker analysis techniques (e. g. the invention of DNA chips for genomic selection) and improvement on the bioinformatics sector regarding scanning methods for SNP detection make SNP marker technology a very important tool for plant genotyping with a very high accuracy and sensitivity (FAO 2011, p. 144; Azhaguvel et al. 2006; Lidder, Sonnino 2011).

**What is a genetic map?**

A genetic map illustrates the genome of a genotype displaying the different chromosomes (\(\pm\) in case of genetic mapping also called “linkage groups”) and is comparable with a “road map” with defined positions or “landmarks” distributed all over the linkage groups (Collard et al. 2005). The “landmarks” are represented by molecular markers whose positions have been estimated by molecular marker analysis in the laboratory, followed by statistical calculations using specific mapping software (Jones et al. 1997; Brumlop, Finckh 2011). At this point it is very important to note that the positions of the markers shown on the linkage groups of a genetic map rely on statistical calculations and thereby only represent estimated values but cannot be compared with the real physical positions of the tested DNA-markers on the chromosomes (Jones et al. 1997).

Distances between markers on genetic maps are specified by “Centi Morgan” (cM) which represents a statistical likelihood of recombination events between markers loci that are located on a linkage group. Recombination goes back to the event of “meiosis”, the production of gamete cells, in which the diploid set of chromosomes (2n) of a genotype is 1) reduced to a haploid set (1n; gamete cells are normally haploid) and 2) recombined. Recombination occurs during chromosome pairing in meiosis when the arms of homologous chromosomes overlap, break and are finally substituted by DNA-repairing
mechanisms of the cells (Dirks et al. 2009). The overlapping- and recombination event of chromosome parts is called “crossing over” and represents a vital evolutionary event for maintaining genetic diversity (Collard et al. 2005). The bigger the cM-distances between marker loci are the more likely is a recombination of two loci alleles among each other during meiosis. In the beginning of constructing a genetic map, a mapping population has to be created by crossing two homogzygous, genetically different parental lines. The F1-population is then backcrossed with one of the parental lines. Because it is necessary to ensure that the tested genotypes in the mapping population are homozygous, the F1-population is either selfed for at least six to seven times (until F6-F7 generation), resulting in a so-called “backcross population” or a DH-population based on the F1-population is created (see chapter 3.3.2). Genetically, the mapping population includes all recombination events that happened during meiosis of the parental lines before crossing. After creation of the mapping population, its DNA is analysed and the population is thereby genotyped, using a whole set of molecular markers. In this connection a DNA-marker can only occur in the shape of either parent A or parent B of the population.

Testing the population with numerous markers results in a dataset consisting of A’s and B’s. This represents the basis for calculations of statistical software which then allocates the particular markers to linkage groups and estimates their positions on the chromosomes. The calculations rely on the recombination events of the marker-loci among each other in the mapping population (Jones et al. 1997). Figure D3 shows exemplary a genetic map, consisting of 5 linkage groups (or chromosome) with 26 mapped markers.

**Figure D3: Hypothetical genetic map**

![Hypothetical genetic map](image)

Note: Hypothetical genetic map showing 5 linkage groups (chromosomes) with 26 mapped molecular markers, labeled with A–Z; the numbers define the distances between the markers in Centi Morgan (cM)

Source: Collard et al. (2005)
It is important to note that every genetic map is unique and only reliable for the tested mapping population. Experiments using the same markers for mapping in different mapping populations may, or even will, result in differences in the calculated map. Amongst other things, this also depends on the performance of the used DNA-markers for mapping in different genotypes. Especially RFLP- and SSR-markers show a proper stability concerning their approximate positions among different genetic maps and are therefore called “anchor”-markers (Collard et al. 2005).

Quantitative trait loci (QTL) mapping

Many complex traits in crop plants, such as yield, the substantial composition of the product or tolerance to drought or coldness not only depend on one particular gene but are mostly affected by numerous genes and their interaction amongst each other and with the environment. A region in the genome affecting the expression of these complex quantitative traits is called a “Quantitative Trait Locus” (QTL) (Doerge 2002).

Collard et al. (2005) compare identification of a gene or a QTL within a plant genome with “finding the proverbial needle in a haystack” and define QTL analysis as “the principle of detecting an association between phenotype and the genotype of marker”. QTL analysis is based on genetic mapping (as described above) and combines the genotypic data with measured phenotype values (Jones et al. 1997). Therefore, additionally to the genotypic information, phenotypic data of the trait of interest is collected in the mapping population that has been derived from two parental lines. For QTL analysis it is very important that the parental lines strongly differ in the trait of interest. As an example, one would chose a very tall parental line A and a dwarf parental line B for QTL analysis for the trait “plant height” to get a broad distribution of the characteristic of the trait in the mapping population. After data collection, special QTL mapping programs calculate the correlation between the expression of the trait (phenotype) and the shapes of all tested markers (genotype). There are several QTL calculation methods, starting with the first invented method “single marker analysis”, “simple interval mapping” (SIM), “composite interval mapping” (CIM) or modern more complex methodologies like “multiple interval mapping” (MIM) (Doerge 2002). QTL analysis results in the finding of one or more regions in the genome that probably have an influence on the expression of the trait of interest, if the software can statistically identify a QTL (Collard, Mackill 2008).

Finding suitable markers for marker-assisted selection

The calculated QTL regions are more or less closely flanked by molecular markers that have previously been mapped in the mapping population. When a marker is located close to a QTL it is considered to be linked to the QTL and therefore together inherited with it.

“Marker-assisted selection” (MAS) follows the aim to use the shape of these particular QTL flanking markers (in analytical methods) as a basis for selection. Those plants showing promising genetic compositions are considered to carry those genes that are involved in causing a favorable expression of the traits of interest. The tighter the linkage of a QTL and its flanking marker is, the more promising is the selection for the trait based on the marker genotype (Jones et al. 1997). Recombination can also occur between a QTL and its flanking marker and is more likely, when both loci are located more distantly, thereby making the marker valueless for selection for a particular trait (Collard, Mackill 2008). However, choosing big mapping populations and genetic maps with high numbers of markers covering the genome with a high density (< 1 cM distance between neighboring markers; also called “fine mapping” or “high-resolution-mapping”) for QTL analysis can enhance the accuracy of the QTL detection method (Collard et al. 2005).

It is important to state that genetic maps derived from particular mapping populations are unique and not automatically assignable to other populations. The QTL results also have a unique character. This means, that even if significant QTL for a particular trait could be mapped in a mapping population and there are markers that are located very close to the QTL, the QTL flanking marker is not automatically suitable for MAS. That’s why markers have to be tested intensely before they can be taken as applicable.
for MAS. Collard and Mackill (2008) describe this process as “marker validation”, in which the candidate markers are tested in differing important breeding material. For practical reasons, it is also important to provide a “toolbox” of polymorphic markers for MAS to broadly and densely span and flank the QTL region because individual markers may have limited polymorphisms in different genotypes and are therefore not suitable in every breeding material.

3.5 Breeding with genetic modification of crop plants

In the history of development of plant breeding techniques, genetic engineering and DNA recombinant techniques came up in the 1980s (Lusser, Parisis 2011). Their aim is to straightly transfer genes of interest to plants to create improved varieties and thereby passing the procedure of crossing and selection steps in conventional breeding methodologies and also passing natural crossing barriers (Acquaah 2007, p. 9; Mehetre, Aher 2004). Plants generated by using genetic engineering are called “genetically modified (GM) crops” and are estimated to have been cultivated on 170 million hectares in 2012 worldwide (James 2012).

GM crops of the so-called “first generation” aimed at improved agronomic characteristics such as higher crop yields, resistance to pests or optimising agricultural cultivation. “Second-generation” GM crops will feature increased nutritional and/or industrial traits, for example rice enriched with iron and vitamins, potatoes with higher starch content and inulin, allergen-free nuts or healthier oils from soybean and rapeseed (Sauter, Hüsing 2005; James 2011). Today, only two genetically transferred traits account for 99.9 % of the cultivated GM crops, namely “Herbicide Resistance (HR)” and Bacillus thuringiensis (Bt)-insect-resistance, which are either solely present or combined in the particular GM crops (Sauter 2008, p. 7). Only four GM crop species, soybean, maize, cotton and rapeseed, are grown on almost entirely area cultivated with GM crops.

There are two approaches of genetic transformation of plants depending on the origin of the particular gene of interest, the “transgene” and the “cisgene” approach. In the transgene approach the gene of interest origins from an organism that is not related with the plant species (e.g. bacteria) and can therefore not naturally be combined with it. In the cisgene approach the gene of interest origins from a closely related plant species that could naturally be crossed with the crop plant that shall be genetically modified (Venkatesh, Strauss 2010).

The general approach of genetic transformation of a plant can be divided into the following main steps (Figure D4):

> Identification and isolation of the gene of interest (transgene or cisgene)
> Cloning of the transgene by inserting it into a cloning vector, a special DNA molecule that carries the transgene and transferring it to a host cell that represents the vector of the transgene, replicating and thereby maintaining the cloning vector.
> Transferring the transgene and identification and isolation of transformed plant cells for further cultivation and propagation.
Identification and isolation of genes of interest

Several methods to identify a gene’s function have been developed over the past decades. There are two main approaches for revealing the function of a gene, either based on the gene product or based on the DNA sequence (Acquaah 2007, p. 234). Due to the immense progress in sequencing technologies, the establishment of DNA libraries for various important crop plants, the improvement of the bioinformatics sector and open access databases with sequence information for nearly all crop plants scientists nowadays have numerous tools for estimating and predicting the function of a particular DNA sequence. More detailed information about identification of gene functions are given by Acquaah (2007, p. 233-234) or Baxevanis (2004).

Once a gene of interest is identified it has to be isolated from the genome of the organism that carries it. This is achieved by extracting the genomic DNA of the source organism and then using specific DNA cutting enzymes (restriction enzymes) that cut out the specific DNA sequence (ISAAA 2010).

Cloning of a transgene

Because a piece of DNA cannot self-replicate, the isolated transgene has to be integrated in a cloning vector, a piece of DNA carrying important sequence characteristics that mediate it’s replication in the target cell (Acquaah 2007, p. 233). Cloning vectors that have been widely used in genetic engineering are plasmid vectors. Plasmid vectors, which originate from bacteria, are circular double-stranded, self-replicating DNA-molecules with selectable marker genes (selectable marker genes are explained in step “Identification of transformed plant cells”) (ISAAA 2010). To infiltrate the target DNA sequence in the plasmid vector, the vector is cut with a specific restriction enzyme, causing specific sequence overlaps (also called “sticky ends”) at the cutting sites. These overlaps are complementary to those of the target DNA sequence produced during transgene isolation in the beginning. By complementary fitting of the sticky ends of both, the plasmid vector and the target sequence (the transgene) can be inserted into the
plasmid vector by endogenous DNA repairing enzymes. The plasmid vector is then transformed into bacteria cells that produce thousands of copies of the cloning vector in culture medium (Suslow et al. 2002). Depending on the applied DNA transferring technique (see below) the vector plasmids can be isolated from the bacteria cells after being replicated.

**Transfer of a transgene and identification of transformed plant cells**

DNA sequences can be transferred to plant cells either directly or in a mediated way. The most frequently used approach for directly transferring DNA sequences to plant cells is “particle bombardment”. In this approach plant cells are literally been shot with gold or tungsten particles that carry the target DNA, using a biolistic device, a so-called “gene gun”. Within approximately 12 hours the inserted DNA gets inside the nucleus of the plant cell and is integrated in the DNA of the plant (Acquaah 2007, p. 234; Schlegel 2010, p. 53; ISAAA 2010). Further methods for direct gene transfer are electroporation, micro-injection or silicon carbide procedures (Acquaah 2007, p. 234).

In approaches in which the DNA transfer to plant cells is mediated, vectors are used as couriers that carry the target DNA into the cell. The most common practice used for the production of genetically modified transgenic crops is the Agrobacterium-mediated gene transfer (Tzfira, Citovsky 2006). Agrobacterium tumefaciens is a plant pathogenic bacterium that has the ability to transfer DNA to plant cells. In its natural form it causes gall formation of plants by introducing its tumor-inducing (Ti) plasmid to the plant cell and thereby affecting the hormonal balance of a plant (Einset 1982). By modification of its genetic composition and replacing the tumor-inducing site of the Ti plasmid with a gene of interest, *A. tumefaciens* turned from a plant pathogen into an important tool for genetic engineering of plants (Tzfira, Citovsky 2006).

The bacterium’s plasmid is modified in a way that besides the gene of interest it also carries selectable marker genes and reporter genes. The selectable markers mediate resistances against for example non-medically important antibiotics which are used in the plant cell cultivation medium after transformation to select only those cells which carry the selectable marker sequence. This indicates the presence of the target gene in the cell (Tzfira, Citovsky 2006). The reporter genes encode fluorescing proteins that can be detected under special light and are only present in those plant cells that have successfully been transformed with the gene of interest (ISAAA 2010).

There are different practical techniques to transform plants using *A. tumefaciens*-mediated gene transfer. One common approach is the “leaf disk method” in which plant leaves are cut in small quadratic pieces and are co-cultivated with *A. tumefaciens* in culture medium (Acquaah 2007, p. 235). The bacterium has special tools for detecting wounded sites of plants material and inoculates plant cells at the cutting sites (Einset 1982). After two days of infiltration the leaf disks are transferred to a new regeneration medium that also contains substances like non-medically important antibiotics which will cause shrinkage of cells which failed a correct transformation and do not carry the target gene. Using established tissue culture methods, it is possible to generate whole plants out of single cells that are genetically modified (Suslow et al. 2002; ISAAA 2010; Tzfira, Citovsky 2006).

**New plant breeding techniques**

Besides the cisgenesis-/intragenesis-approach, there are further novel and very promising GM techniques in the pipeline, being intensively explored in research. Like in classical GM techniques most of them are used to enhance genetic variation and to directly modify specific genes of interest. According to studies that summarised the impact and usage of new GM techniques, the “targeted” (or “site-directed”) mutagenesis approach is of high importance. The principle of this approach follows the aim to either directly switch-off particular genes, induce mutations or insert new genes in specific parts of the DNA sequence, mostly using specific DNA cutting enzymes. These enzymes are modified and carry DNA sequences that are complementary to the target sequence which guides them to the gene of interest, thereby acting site-specific. The breakage of the DNA strand is then repaired by endogenous DNA repairing enzymes which re-bind the DNA cutting sites. As these cutting sites are usually uneven
and not homologous the cutting and repairing of the sequence results in a mutation. The most important methods in this context is the “Zinc finger nuclease 1/2” (ZFN-1/-2) technique and the Oligonucleotide directed mutagenesis (ODM) approach. Another important technique to directly and site-specific switch-off genes is the RNA-dependent DNA methylation (RdDM) (Lusser et al. 2011, pp. 23-27).

Other approaches within targeted mutagenesis go further by combining DNA cutting enzymes that are highly specific for particular DNA sequences or genes with DNA molecules or genes that shall be assembled into the sliced DNA sequence by endogenous DNA repairing enzymes. In this context the “Zinc finger nuclease 3” (ZFN-3) technique is applied to a wide extent in modern GM research.

Another modern upcoming approach is “Agroinfiltration”. This technique is mostly used to study plant-pathogen interaction in living tissues (leaves) or to test the functionality of regulatory elements in gene constructs. Furthermore it can be used to easily create GM plants that however do not differ from classical plants produced by genetic modification.

Much attention has also been given to “Grafting on GM rootstock” which means, that non-GM plant parts are grafted on genetically modified rootstocks that can be produced by classical or modern techniques, for example carrying resistances to soil borne pathogens or improved rooting capacity. When a non-GM scion is grafted onto a GM rootstock, leaves, stems, flowers, seeds and fruits would not carry the genetic modification with respect to changes in genomic DNA sequences (Lusser et al. 2012).

The last important modern approach is “Reverse breeding”, in which generally speaking meiotic activity in heterozygous elite lines is suppressed using genetic modification. The aim is to produce homozygous high-performance lines, also using tissue culture-based methods like the DH technology (Lusser et al. 2011, pp. 23-27).

The breeding goals for which the new techniques are applied are diverse. Some recent examples of the application of modern techniques for traits are given in figure D5.
3.6. Participatory plant breeding

The term “Participatory plant breeding” (PPB) describes breeding approaches that involve collaborations between practical breeders or researchers and farmers with the aim to genetically improve agronomic important plant species (Schlegel 2010, p. 264 and 265). In PPB programs the breeding process is decentralized which means that the management and responsibility for a breeding program not only rests with the plant breeder like in traditional breeding projects, but is distributed to farmers that are strongly involved in the breeding program (Acquaah 2007, p. 464).

PPB thereby covers all steps in the research and development cycles of creating new improved varieties (Kotschi 2010). The concept of PPB emerged in the 1980s and originally tried to address the needs of poor farmers in developing countries (FAO 2009), thereby keeping close relation to local cultures and the knowledge and skills of the farmers (Weltzien, Christinck 2009, p. 78). The involvement of the farmer in the breeding program can take different forms. It could be consultative in a way that the farmer is interviewed on the performance of test varieties he tests in his fields or on agro-ecological issues. More active forms of farmer participation could be that the farmer is fully included in the practical breeding process, for example in terms of participating in the planning phase of a breeding program, creating new...

---

Figure D5: Most relevant crops and traits resulting from the use of new plant breeding technologies

<table>
<thead>
<tr>
<th>Technique</th>
<th>Crop</th>
<th>Traits</th>
<th>Number of research papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>22N</td>
<td>Maize</td>
<td>Herbicide tolerance</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tobacco</td>
<td>Herbicide tolerance</td>
<td>3</td>
</tr>
<tr>
<td>GDM</td>
<td>Maize</td>
<td>Herbicide tolerance</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Rice</td>
<td>Herbicide tolerance</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tobacco</td>
<td>Herbicide tolerance</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Oilseed rape</td>
<td>Herbicide tolerance</td>
<td>1</td>
</tr>
<tr>
<td>Gmogenesis intragamet</td>
<td>Potato</td>
<td>Fungal resistance; black spot brown tolerance; lower acrylamide levels</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Apple</td>
<td>Fungal resistance</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melon</td>
<td>Fungal resistance</td>
<td>1</td>
</tr>
<tr>
<td>1Rd21M</td>
<td>Maize</td>
<td>Male sterility</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>MODIFIED starch content</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Petunia</td>
<td>Redpapered flower pigmentiation</td>
<td>1</td>
</tr>
<tr>
<td>Grafting on GM rootstock</td>
<td>Grapes</td>
<td>Resistance against bacteria, fungi and virus, root ability</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Pork</td>
<td>Resistance against fungi and virus, changed composition</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Apple</td>
<td>Rooting ability</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Watermelon</td>
<td>Robust growth; virus resistance</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Cucumber</td>
<td>Fungal resistance; cosmetic control</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>Virus resistance</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Plum</td>
<td>Resistance against fungi and nematodes</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Walnut</td>
<td>Rooting ability</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pea</td>
<td>Virus resistance</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rose</td>
<td>Rooting ability</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tobacco</td>
<td>Resistance against bacteria</td>
<td>1</td>
</tr>
<tr>
<td>Agro-infestation</td>
<td>Tomato</td>
<td>Production of vaccines (hepatitis B, screen for virus resistance)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Tobacco</td>
<td>Production of vaccines (hepatitis B, HIV, diabetes, influenza, trispinoma, talarus, tuberculin, SARS, New Canna disease, Norwalk virus, antibodies (HIV, hepatitis, cancer, blood typing, cardiovascular), therapeutically proteins and enzymes, screen for resistance against fungi and virus)</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>White clover</td>
<td>Production of vaccines (bovine parvoviruse)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Lettuce</td>
<td>Production of vaccines (SARS)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rice</td>
<td>Screen for virus resistance</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Bean</td>
<td>Screen for virus resistance</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>Screen for resistance against fungi and virus</td>
<td>3</td>
</tr>
</tbody>
</table>

Note: Source: Lusser et al. (2012)

---

Reverse breeding is not included because no research papers on specific plants have been identified.
variations, conducting trial management or taking part in the selection step to isolate promising genotypes with favourable performances in the testing fields (Kotschi 2010; Weltzien, Christinck 2009, p 78).

Especially in marginal regions with specific environmental conditions, PPB can contribute to a narrow adaptation of a cultivar to the target environment and thereby serve the specific needs of a farmer which is stated as a great advantage of PPB, especially for developing countries with challenging conditions for plant cultivation (Weltzien, Christinck 2009, p. 81). There are reports and case studies about PPB programs that took place in Nepal, Syria, Tunisia, Morocco, Cuba, China, India, Honduras and Nicaragua in which the successful application of PPB led to improvement of different important crop plants, such as rice, maize or soybean (Vernooy et al. 2009, pp. 617-626). The PRGA program (2009) states that there were around 100 PPB programs worldwide being implemented in 2009.

3.7 Breeding in organic farming

Seeds that are produced for crop cultivation in organic farming are subject to requirements that have to be fulfilled to make them suitable for crop growing under organic conditions. Therefore, the breeding process has to be adapted to the accounts of organic farming which are defined by the EU Regulation 2092/91, the requirement for all producers to use organic seed (Wyss et al. 2001). Besides the regulations concerning the breeding techniques that are suitable for seed production in organic farming, the breeding goals also differ from those defined for conventional farming as there are distinct differences regarding the crop production conditions between conventional and organic farming (Lammerts van Bueren et al. 1999, p. 5).

The plants that are cultivated in organic farming must be adapted to the specific conditions in the cultivation area because, for example, the application of chemical plant protective agents or synthetic fertilizers is not allowed in organic farming. Considerations that are particularly important for developing varieties suited to organic conditions are high resistances and tolerances to biotic stresses, a high adaptation to local climate and nutrient dynamics, a high nutrient efficiency and a high yield stability and storability of the product (Wyss et al. 2001).

Generally, plant breeding has largely developed in response to the demands of intensive agriculture over the last 60 years. For a long time organic farmers had to make use of traditionally bred varieties which led to the general question, whether these varieties truly fulfill the needs of organic production. Furthermore, these varieties were developed for conventional farming systems that generally aim to maintain good growing conditions and to reduce stress factors. Whereas genetically modified crops were and are strictly forbidden in organic crop production, in the past organic farmers could sow conventional produced seeds with some restrictions: The parent plants of annual crops had to be grown for at least one generation under organic conditions, parents of biannual and perennial varieties had to be grown for at least two years under organic conditions (Wyss et al. 2001, p. 2).

Since 2004 organic producers have to use only organic seeds and vegetative multiplication material. However, over 95% of those varieties that are cultivated organically were initially bred for conventional farming systems. Furthermore, because of the limited markets for organic seeds and the high expenses of registering a variety, private-sector breeders generally cannot spend more than 10% of their investments on organic seed production (Dawson et al. 2011).

The available breeding techniques for creating organic seeds do not completely vary from the conventional ones. Besides the prohibition of genetic engineering techniques in organic breeding and the consideration for plant adaptation to special organic production conditions, organic seeds have to meet the demands of the maintenance of integrity of plants, which represents one major principle of organic farming (Acquaah 2007, p. 468 and 469). This means that those techniques that artificially disrupt the genetic makeup of a plant or disturb or manipulate its natural growth, development and propagation are prohibited as well as techniques that are used in conventional plant breeding for doing wide crosses
between unrelated species to overcome natural crossing barriers (Lammerts van Bueren 1999, p. 6; Wyss et al. 2001, p. 22 and 23). However, techniques that are compatible with plant integrity, like marker-assisted selection, are suitable for organic plant breeding, because they represent diagnostic tools and do not cause genetic modification of the plants (Acquaah 2007 p. 469).
REFERENCES


Lidder, P., Sonnino, A. (2011): Biotechnologies for the management of genetic resources for food and agriculture. FAO (Food and Agriculture Organization of the United Nations) Background study paper no. 52, part of the cross-sectoral theme “Application and integration of biotechnologies in the conservation and utilization of genetic resources”.


PRGA (Participatory Research and Gender Analysis) Program (2009): *Participatory plant breeding*. PRGA Program Thematic Brief No. 2. CGIAR Systemwide Program on Participatory Research and Gender Analysis. Cali, Colombia.


Technology options for feeding 10 billion people

Plant breeding and innovative agriculture

Annex E: Reducing Food Losses
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APHLIS  African Postharvest Losses Information System
BRIC  Brazil, Russia, India and China
CA  Controlled Atmosphere
CEE  Central and Eastern European Countries
CIS  Commonwealth of Independent States
ECS  Evaporating Cooling System
FFV  Fresh Fruits and Vegetables
FSC  Food Supply Chain
GMO  Genetically Modified Organism
MAP  Modified Atmosphere Packaging
RA  Regular Air/Atmosphere
ULO  Ultra Low Oxygen
WFC  World Food Conference
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1. INTRODUCTION

There are three types of discourses on food waste:

> on estimating crop/food losses for better storage, marketing and delivery planning;
> on highlighting the scale of food waste in relation to global malnutrition (moral and economic perspective); and
> on proposing technical solutions in order to control food losses and hence, to increase food supply.

The latter is the most relevant to this study, while the publications on the two former provide important information on the situation.

Parfitt et al. (2010) distinguishes between food losses and food wastes, arguing that the former relates to early stages of the food supply chain (FSC) and refers to a system which needs investment in infrastructure\(^1\). In contrast, the term food waste is applied to later stages of the FSC, and generally relates to behaviour of food suppliers and consumers. This study concentrates on harvest and post-harvest crop losses before the raw material reaches processing. In the analyses are included losses which occur in the first four stages of the FSC as described in Table E1.

### Table E1: The scope and the structure of crop losses in this report

<table>
<thead>
<tr>
<th>Stage of the FSC</th>
<th>Examples of food loss characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Harvesting—handling at harvest</td>
<td>Edible crops left in field, ploughed into soil, eaten by birds, rodents, timing of harvest not optimal: loss in food quality, crop damaged during harvesting/poor harvesting technique, out-grades at farm to improve quality of produce</td>
</tr>
<tr>
<td>2 Threshing/shelling/chaff separation</td>
<td>Loss through poor technique</td>
</tr>
<tr>
<td>3 Drying/curing/cooling, transport and distribution</td>
<td>Poor transport infrastructure, loss owing to spoiling/bruising</td>
</tr>
<tr>
<td>4 Storage</td>
<td>Pests, disease, spillage, contamination, natural drying out of food</td>
</tr>
</tbody>
</table>

**Source:** Based on Parfitt et al. (2010)

The last two stages (3 and 4) cannot always be clearly separated from primary processing and so do the losses.

Crops are lost also during the growing phase due to adverse weather events like droughts, heavy rains and floods, hailstorms and frosts which frequency and magnitude are associated with climate change (Dusseldorp, Sauter 2011). The disaster is often amplified by factors such as changes in landscape, soil structure (organic matter in soil, compaction), water regime, soil erosion, and crop varieties which might not be fully suitable. These losses before harvest are part of the yield gap and will be discussed in topic 2 of this study.

---

\(^1\) “Investment in infrastructure” is understood in broader terms as investment in knowledge, technology, and transport and market infrastructures.
Reduction of food losses is within the mandate of the Food and Agriculture Organization of the United Nations (FAO). In 1974, the first World Food Conference (WFC) identified reduction of postharvest losses as one of the actions which might significantly contribute to the reduction of world hunger. At this time, postharvest losses were estimated at 15% and the proposal settled at the WFC was to reduce them by half by 1985 (Parfitt et al. 2010). Initially, the main focus of the Special Action Programme for Prevention of Food Losses was only on reducing losses of durable grain; later (in the 1990s), the scope of work had been broadened to cover roots and tubers, and fresh fruits and vegetables (FFVs). However, the lack of adoption of effective measures led to no progress in reduction of post-harvest losses. The poor performance of the Special Action Programme can be accounted to purely technical perception of the food losses problem. Instead, a more holistic approach is needed (Grolleaud 2002). Following this understanding, this report will not only identify gaps in technology and marketing infrastructure, but will also discuss organizational and institutional imperfections which prevent transfer of knowledge and investment in reducing crop losses effectively anywhere in the world.

The focus of this study is on three categories of crops:

> grains (cereals and oilseeds),
> roots and tubers and
> fresh fruits and vegetables (FFV).

They differ in a number of characteristics of which the degree of perishability (Table E2) is one of the most important from the post-harvest losses point of view. On one pole there are grains, on the other pole highly perishable fresh fruits and vegetables, root and tuber crops are in-between.
### Table E2: Product characteristics relevant to food supply chains and food losses

<table>
<thead>
<tr>
<th>Categories of crops</th>
<th>non-perishable (grains)</th>
<th>perishable food crops (FFV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest</td>
<td>seasonal, but possibility of permanent or semi-permanent production</td>
<td>drying for long term storage, washing</td>
</tr>
<tr>
<td>Preliminary treatment</td>
<td>threshing, drying (if needed), cleaning</td>
<td>cleaning</td>
</tr>
<tr>
<td>Fruit</td>
<td>seasonal, but possibility of permanent or semi-permanent production</td>
<td>drying for long term storage, washing</td>
</tr>
<tr>
<td>Product moisture</td>
<td>small (below 1 g)</td>
<td>large (5 g - 5 kg)</td>
</tr>
<tr>
<td>Respiratory activity of stored products</td>
<td>low</td>
<td>high (50-80%)</td>
</tr>
<tr>
<td>Tissue</td>
<td>hard, good protection</td>
<td>soft, highly vulnerable</td>
</tr>
<tr>
<td>Storage</td>
<td>long term (due to seasonality), good natural disposition</td>
<td>rather short term</td>
</tr>
<tr>
<td>Losses during storage</td>
<td>mainly from exogenous factors</td>
<td>both endogenous (respiration, transpiration, germination, etc.) and exogenous factors</td>
</tr>
<tr>
<td>Direct consumption</td>
<td>rare (need processing)</td>
<td>products for direct consumption</td>
</tr>
</tbody>
</table>

**Note:** Exogenous factors: pests, insects, rodents, stealing, etc.

**Source:** Based on Parfitt et al. (2010)

Both quantitative and qualitative food losses are considered in the literature. However, not all weight losses are necessarily food losses. Weight decreases due to respiration and transpiration might be considered as natural, as long as they have no effect on the quality and the opportunity to sell crops. Similarly, the loss of weight due to drying cannot be regarded as food loss (Hensel 2009). Degradation in quality usually results in impossibility to market such crops. Quality criteria depend on the use of crops and societal/consumer concerns; they include physical and chemical properties, colour, shape, size, nutritional value or absence of microorganisms, toxins and other pollutants (Hensel 2009).

The food supply chains, which include post-harvest technologies and marketing organization and infrastructure, are to large extent determined by product characteristics associated with perishability (Table E3).
Table E3: Characterisation of the development stages of food supply chains (FSCs)

<table>
<thead>
<tr>
<th>Class of countries</th>
<th>Developing</th>
<th>Transitional (e.g. BRIC)</th>
<th>Developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income</td>
<td>small holders, semi-subsistence farms</td>
<td>dual farm structure, semi-subsistence farms and larger commercial farms</td>
<td>medium and farms and large commercial farms</td>
</tr>
<tr>
<td>Transitional (e.g. BRIC)</td>
<td>mechanised harvesting alongside the traditional systems</td>
<td>harvesting highly mechanised</td>
<td></td>
</tr>
<tr>
<td>Developed</td>
<td>medium and farms and large commercial farms</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FSC characteristics</th>
<th>Class of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of growers</strong></td>
<td>Developing</td>
</tr>
<tr>
<td></td>
<td>Transitional (e.g. BRIC)</td>
</tr>
<tr>
<td></td>
<td>Developed</td>
</tr>
<tr>
<td>Low income</td>
<td>small holders, semi-subsistence farms</td>
</tr>
<tr>
<td></td>
<td>dual farm structure, semi-subsistence farms and larger commercial farms</td>
</tr>
<tr>
<td></td>
<td>medium and farms and large commercial farms</td>
</tr>
<tr>
<td>Transitional (e.g. BRIC)</td>
<td>mechanised harvesting alongside the traditional systems</td>
</tr>
<tr>
<td>Developed</td>
<td>harvesting highly mechanised</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Harvesting technology</th>
<th>Class of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income</td>
<td>traditional, often manual or simple mechanisation</td>
</tr>
<tr>
<td>Transitional (e.g. BRIC)</td>
<td>mechanised harvesting alongside the traditional systems</td>
</tr>
<tr>
<td>Developed</td>
<td>harvesting highly mechanised</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Postharvest infrastructure</th>
<th>Class of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income</td>
<td>traditional threshing, drying, storing, simple mechanisation</td>
</tr>
<tr>
<td>Transitional (e.g. BRIC)</td>
<td>intermediate i.e. a mixture of sophisticated and traditional technologies</td>
</tr>
<tr>
<td>Developed</td>
<td>sophisticated technologies, cold chains</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Marketing system</th>
<th>Class of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income</td>
<td>local markets</td>
</tr>
<tr>
<td>Transitional (e.g. BRIC)</td>
<td>local, urban and increasingly export markets</td>
</tr>
<tr>
<td>Developed</td>
<td>centralised (supermarkets), export orientation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level of vertical integration</th>
<th>Class of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income</td>
<td>poor integration, many intermediaries supplying urban markets</td>
</tr>
<tr>
<td>Transitional (e.g. BRIC)</td>
<td>vertical coordination, less intermediaries</td>
</tr>
<tr>
<td>Developed</td>
<td>high vertical integration, even supranational</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quality</th>
<th>Class of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income</td>
<td>variable quality, no requirements on standards</td>
</tr>
<tr>
<td>Transitional (e.g. BRIC)</td>
<td>variable quality, standards for export markets</td>
</tr>
<tr>
<td>Developed</td>
<td>quality and safety standards central to the FSC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Level of urbanisation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Diversification of diet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Globalisation (integration in the World trade)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Own illustration based on Parfitt et al. 2010

Many authors (e.g. Hensel 2009; Hodges et al. 2010; Parfitt et al. 2010) point out that the nature of food losses and food waste depends on the stage of the development of FSC. Basic characteristics of FSC (without their further differentiation by the above mentioned product groups) are summarized in Table
In general, the transition of FSCs goes from traditional semi-subsistence system toward highly integrated global food supply system.

Parfitt et al. 2010 distinguishes three main global drivers of the development of FSC: urbanisation and declining share of the agriculture in GDP, dietary transition and increasing globalization of trade. While dietary transition in developing/transitional countries results from urbanization (change of live style) and growing income, ageing of population is an important factor of it in developed countries. Hodges et al. 2010 describes that main food losses are due to spillage and biological spoilage in the first stages of the FSCs in developing countries; in contrast, the critical factor for food losses/wastes is in developed counties the growing intolerance of cosmetic defects or deviations from substandard food traits. Table E3 can be interpreted in the way that FSC chains in the developed countries are already results of the mentioned three global trends, while the other two FSC are at the early and progressed transition due to these drivers.
2. OVERVIEW OF HARVEST AND POSTHARVEST CROP LOSSES

Most authors agree on the difficulty and rather low reliability of the estimates of post-harvest losses. Measuring what has been lost implies that it is known what was there at the outset and this is usually not the case (Hoddges et al. 2010). Basically, two main approaches are adopted to estimate post-harvest losses: either to actually measure what has been lost or to use questionnaires to collect subjective loss estimates from those who have experienced them. The problem is that throughout the citations and transcriptions this basic methodological information is lost. In addition, some authors (e.g. Gustavsson et al. 2011) add their own assumptions which are based on similarities with other production systems and regions. There are differences among authors (and thus figures) in terms of operations which have been included in post-harvest handling (Grolleaud 2002).

Figure E1: Variation of weight loss during storage

![Variation of weight loss during storage](source: Own illustration based on Remboldt et al. (2011))

Figure E1 provides an illustration of the variability of crop loss estimates for storage of cereals on small farms in the approximately homogenous regions in terms of climate, economic development and cultural aspects. Thus the variance likely depends on applied methods (authors), year of the survey and other unreported parameters².

The purpose of estimating food losses is also important: if it is for calculations of food availability, all losses should be included; however, if the estimates should guide actions to combat food losses than they should include only avoidable losses. One has to understand that due to mechanical or biological processes (e.g. respiration) some post-harvest losses are unavoidable (Grolleaud 2002). Also social contexts might be important in determining what food loss is and what not (important when subjective judgments are surveyed).

² As note by Tyler (1982) “postharvest losses may be due to a variety of factors, the importance of which varies from commodity to commodity, from season to season, and to the enormous variety of circumstances under which commodities are grown, harvested, stored, processed and marketed.” It is therefore important not only to work with figures that are good estimates at the time and in the situation they are taken but to be aware that at other times and situations the figures will differ.
2.1. Estimations of post-harvest losses

In this paragraph, assessments of postharvest losses are presented by commodities or groups of commodities, macro regions\(^3\), countries and by climatic and weather conditions. Macro regions refer primarily to various levels of the development of FSCs and their economic environment worldwide, nevertheless, when interpreting the figures one has to take into account also climatic differences.

The importance of harvest and post-harvest losses within the FSC and within food losses/wastes in different commodity chains is illustrated in Figure E2. The percentage distribution of food losses is based on the extensive work of Gustavsson et al (2011). The advantage of Gustavsson’s study is that it provides “complete” geographical coverage (differentiated by macro-regions). However, the authors do not hide that their estimates are based on various sources and sometimes on their own judgments. A certain level of consistency is guaranteed by using exclusively FAO data on food production and consumption and by assuring balance between production, use and losses at each stage of the FSCs.

It is obvious that there are substantial differences in harvest and post-harvest losses between developed (the three left columns in each graph) and developing and transitional countries. Particularly post-harvest losses are very low (6-14% of all food losses) for all three commodity groups in developed countries, while these might be the most important (up to 44% of all food losses) in less developed regions. This is without doubts due to better post-harvest technologies, particularly storage facilities. However, the temperature and humidity is also an important factor affecting post-harvest losses; these are particularly high for cereals, and root and tuber crops in Sub-Saharan Africa and South and Southeast Asia.

However, regions are still far to be homogenous in terms of economic development and climate. Table E4 present estimates of harvest and postharvest losses in individual countries (without developed countries). These estimates come from various authors, from various periods, using various methodologies. The figures are often presented as ranges, often very broad ranges. We are especially highlighting three of the BRIC countries which are transitional countries (with a transitional FSC). However, they do not differ from the rest of the countries in terms of reported harvest and postharvest losses. At the bottom of the table, scarce estimates of harvest and post-harvest losses of the three former Soviet Union countries (CIS – the Commonwealth of Independent States) are reported. Also these do not differ from the other countries substantially.

---

\(^3\) Groups of countries of similar climatic, geographical and socio-economic characteristics.
Commodity groups:

**Cereals**: wheat, rice (milled), barley, maize, rye, oats, millet, sorghum, other cereals.

**Roots and Tubers**: potatoes, sweet potatoes, cassava, yams, other roots.

**Fruit and Vegetables** (including bananas): oranges and mandarins, lemons and limes, grapefruit, other citrus, bananas, plantains, apples (excl. cider), pineapples, dates, grapes (excl. wine), other fruit, tomatoes, onions, other vegetables.
Source:  Based on Gustavsson et al. 2010

A common observation is that upper ranges of post-harvest losses are pretty large for almost all grains and countries. Although grains are not perishable, substantial part of the high loss figures ought to be accounted to storing. As it will become apparent later, higher storage losses are associated with wet weather (climate), inappropriate post-harvest treatment and poor storage facilities.

Table E4:  Harvest and postharvest losses by countries and commodities

<table>
<thead>
<tr>
<th>Country</th>
<th>Rice</th>
<th>Maize</th>
<th>Wheat</th>
<th>Sorghum</th>
<th>Pulses/oilseeds</th>
<th>Roots and tubers</th>
<th>FFV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Africa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Egypt</td>
<td>2.50%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sudan</td>
<td>17%</td>
<td>6-19%</td>
<td>6-20%</td>
<td>4-27%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nigeria</td>
<td>10-70%</td>
<td>0-40%</td>
<td>5%</td>
<td></td>
<td></td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>Ghana</td>
<td>7-14%</td>
<td>7-45%</td>
<td>15-60%</td>
<td>10-50%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenya</td>
<td>10-23%</td>
<td></td>
<td>10-20%</td>
<td>30-35%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uganda</td>
<td>11%</td>
<td>4-23%</td>
<td></td>
<td>30%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tanzania</td>
<td>20-100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18%</td>
</tr>
<tr>
<td>India</td>
<td>6%</td>
<td>4-8%</td>
<td>2-5.2%</td>
<td>7.50%</td>
<td>4-5.7%</td>
<td>20-30%</td>
<td></td>
</tr>
<tr>
<td>Pakistan</td>
<td>2-10%</td>
<td>2-7%</td>
<td>5-10%</td>
<td>7%</td>
<td>5-10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>6-17%</td>
<td>4%</td>
<td>4%</td>
<td>5%</td>
<td></td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>Malaysia</td>
<td>17-25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20%</td>
</tr>
<tr>
<td>Philippins</td>
<td>9-34%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10-50%</td>
<td></td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>10-40%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20-40%</td>
<td></td>
</tr>
<tr>
<td>Thailand</td>
<td>8-14%</td>
<td></td>
<td>10-30%</td>
<td></td>
<td></td>
<td>20-30%</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>5-23%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10-35%</td>
<td></td>
</tr>
<tr>
<td><strong>South America</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brasil</td>
<td>1-30%*</td>
<td>15-40%*</td>
<td>15-20%*</td>
<td>15-25%</td>
<td></td>
<td>8-10%</td>
<td></td>
</tr>
<tr>
<td>Paraguay</td>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td>15%</td>
<td>17-30%</td>
<td></td>
</tr>
<tr>
<td>Bolivia</td>
<td>16%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>10-25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venezuela</td>
<td>10-25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dom. Rep.</td>
<td>6,5%</td>
<td>9%</td>
<td></td>
<td></td>
<td></td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td><strong>CIS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ukraine</td>
<td>14-32%*</td>
<td>14-32%*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moldova</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5-25%</td>
<td></td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>12-30%</td>
<td>12-30%</td>
<td></td>
<td></td>
<td></td>
<td>30%</td>
<td></td>
</tr>
</tbody>
</table>

* likely improved substantially since it was estimated


2.2.  The dynamics of postharvest losses

Because of lack of consistency in food losses data, it is very difficult to assess the dynamics of postharvest losses. The loss estimates for Ukraine are a good example. The estimates in Table E4 come from the two surveys (Striewe 1998; Shpychak 1998) conducted in 1998. No later figures are available.
However, in the meantime, the postharvest sector got privatized and new (foreign direct) investment has reached the sector (Striewe 2011). It is very likely that storage losses dropped accordingly.

African Postharvest Losses Information System (APHLIS) addresses the need for a systematic survey of postharvest losses – particularly for better forecast of food supply in East and Southern Africa. The longest available time series we found are for maize and wheat (Figure E3). In spite of a period of increased post-harvest losses (2005-2007 for wheat and 2006-2007 for maize), both commodities exhibit a long term decline of losses (the down-sloping trend lines).

**Figure E3: The development of postharvest losses in East and Southern Africa**

![Image of Figure E3 showing the share of total annual production for wheat and maize](source: APHLIS 2013)

The Central Institute of Post-Harvest Engineering and Technology in India reported substantial declines of postharvest losses by 25% for wheat, 50% for rice, 45% for maize and 40% for pulses between 2004 and 2010 (CIPHET(ICAR) 2010).
3. CAUSES OF HARVEST AND POSTHARVEST LOSSES

In general, there are three main types of weight and quality losses: spillage and mechanical damages during harvest and postharvest handling, bio-deterioration due to pests, and consumption by insects, rodents and birds (Rembold et al. 2011; Grolleaud 2002). These losses are affected by a number of natural and socio-economic factors (Table E5). Commodities are differently sensitive to these factors. Usually, big losses are outcome of joint effects of several factors.

Weather is not a factor causing postharvest losses by itself, but it can amplify the malfunctioning of the post-harvest treatment system (incl. storage). A key issue is the weather conditions at the time of harvest. When the crop is still standing in the field, storage pests may make their first attack and when unseasonal rains dampen the crop it will result in some mould growth. All small-scale African farmers rely on sun drying to ensure that their crop is sufficiently dry for storage. If weather conditions are too humid then the crop will not be dried sufficiently and losses will be high (Rembold et al. 2011).

Table E5: Factors affecting harvest and postharvest losses

<table>
<thead>
<tr>
<th>Natural</th>
<th>Socio-economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather and climatic conditions</td>
<td>Outdated or improper technologies on farms or in off-farm storages facilities</td>
</tr>
<tr>
<td>Moisture content at harvest</td>
<td>Transport infrastructure</td>
</tr>
<tr>
<td>Spread of pests, insects, rodents</td>
<td>Pest tolerance of crop varieties</td>
</tr>
<tr>
<td></td>
<td>Human factor / knowledge &amp; skills</td>
</tr>
<tr>
<td></td>
<td>Scale of farming</td>
</tr>
<tr>
<td></td>
<td>Integration of FSC</td>
</tr>
<tr>
<td></td>
<td>Other socio-economic factors</td>
</tr>
</tbody>
</table>

Source: Own classification

An illustrative example of the effect of climate is given in Table E6. Tempered dry winter and hot summer climate exhibit lower losses than arid steppes and tropical savannahs.

Crop vulnerability to weather condition in the post-harvest stage is particularly important in respect to climate change. More frequent adverse weather events not only damage or destroy crops but might bring even more frequent unfavourable conditions for the post-harvest treatment (drying) which then lead to the deterioration of crops during storage and thus to higher food losses.

Table E6: The effect of climate, pest larger grain borer (LGB) and scale of farming on storage losses of maize cobs in East and Southern Africa

<table>
<thead>
<tr>
<th>LGB inf.</th>
<th>Climate type</th>
<th>Farming scale</th>
<th>Variety</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Tropical savannah</td>
<td>small</td>
<td>local</td>
<td>9.7%</td>
</tr>
<tr>
<td></td>
<td>Arid steppe</td>
<td>large</td>
<td>local</td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>small</td>
<td>local</td>
<td>13.3%</td>
</tr>
<tr>
<td></td>
<td>Tropical savannah / tempered dry winter and hot summer</td>
<td>large</td>
<td>local</td>
<td>2.1%</td>
</tr>
<tr>
<td>No</td>
<td>Tropical savannah</td>
<td>small</td>
<td>local</td>
<td>5.3%</td>
</tr>
<tr>
<td></td>
<td>Arid steppe</td>
<td>small</td>
<td>local</td>
<td>4.3%</td>
</tr>
<tr>
<td></td>
<td>Tempered dry winter and hot summer</td>
<td>small</td>
<td>local</td>
<td>3.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>small</td>
<td>HYV</td>
<td>9.5%</td>
</tr>
</tbody>
</table>

HYV – High Yield Variety
Source: Rembold et al. 2011
From Table E6, it is also evident that farm size matters; large farms exhibit substantially smaller losses even when the crop is infested by the pest larger grain borer (LGB). Actually, the losses are smaller on large farms with maize cobs infested by LGB than on small farms clean of LGB. The effect of LGB on small farms can be tremendous – losses can increase more than twice due to it (comparing to small farms with no LGB).

Higher crop yields of cereals, from which results increased harvests, can be associated with greater post-harvest losses under some specific circumstances if there are not facilities available to store grain or grains have to be stored for long time due to market deterioration. This was a serious case in some CIS countries in the past (Striewe 1998; Gorton, White 2007; Satybaladin, Grigoruk 2002). In developing countries, it is more common that serious losses result from agricultural developments for which the farmers are not prepared. These include the introduction of high yielding cereal varieties (HYV) that are more susceptible to pest damage (see Table E6, the storage losses are twice higher for HYV than for the local varieties) or additional cropping seasons that result in the need for harvesting and drying when weather is damp (Rembold et al. 2011).

Returning to a specific case of post-communist counties, Gorton & White (2007) and Satybaladin & Grigoruk (2002) report factors like poor transport infrastructure, badly managed state owned elevators and lack of operational capital (for purchasing energy and fuels) as factors which hinder functioning of FSC causing significant crop losses in both the quantitative and economic terms. According to Gorton & White (2007) and Striewe (2011), the Ukraine FSC has recovered after the privatization of the state companies, however, rather bad situation might still prevail in the other CIS countries like Moldova, Kazakhstan, Uzbekistan etc.

The development of Indian FSC is driven by improving income in urban centres and due to the government’s direct intervention in the grain market (Reardon, Minten 2011). These resulted in a rapid development of food processing industry and the retail sector. In general, it has a positive impact on the farming and post/harvest (pre-processing) sector, particularly through deeper integration of farmers in the marketing chain. However, modern retail establishments often have strict requirements regarding the produce they purchase, and they often procure only better-quality products. This leads to a separation between those who are able to modernise their farm business in order to meet such conditions and marginal farmers. Sector modernisation is reflected in declining loss figures as we pointed out earlier, but one has to keep in mind that the group of marginal farmers continues to suffer high losses and low income.

Brazilian agriculture and food industry benefited significantly from trade liberalization; Brazil is now the fifth largest agri-food producer and exporter in the world (Farina 2001). Globalisation can be regarded as a primary driver of the Brazilian FSC transition, the other very important driver is rural to urban migration and improving income of households (Valdes et al. 2009). While both drivers stimulate production (quantity), the former puts additional pressure on quality assurance, while the latter on diversification of food products. Dramatically developing FSC in turn lead to the reduction of food losses in primary production and post-harvest handling (due to new equipment and facilities). Farms which are unable to participate in this FSC transition are marginalised; on them crop losses will likely stay high or even increase.
4. IDENTIFICATION OF OPTIONS TO REDUCE LOSSES IN AGRICULTURE

The important observation from the above analysis (see Figure E4) is that post-harvest losses depend on the economic development of the country in general and on the development of FSCs and farming structures in particular. It is also true for harvest losses of grains. In contrast, harvest losses of roots and tubers, and fruits and vegetables are similar or perhaps slightly lower in developing countries. This is, because the reduction of post-harvest losses does not benefit so much from advanced technologies and good state of the corresponding technical equipment, transport infrastructure and storage facilities (on farms or between farms and processing industry/retailers). Harvest mechanisation reduces only grain losses, while it likely increases damages on root crops or fruits and vegetables.

Table E7: Technological improvements for reducing food losses

<table>
<thead>
<tr>
<th>Stage (as in Table E1)</th>
<th>Grains</th>
<th>Root &amp; tubers</th>
<th>FFV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Harvesting – handling at harvest</td>
<td>Mechanisation, combine harvesters</td>
<td>Mechanical or chemical vine killing; Harvest mechanisation.</td>
<td>System “field – consumer”</td>
</tr>
<tr>
<td>2 Threshing/shelling/ separation</td>
<td>Mechanisation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a Drying/curing/ cooling</td>
<td>Drying facilities, independent of the sun shine</td>
<td>Curing - wound healing technologies</td>
<td>Pre-cooling facilities *)</td>
</tr>
<tr>
<td>3b Transport and distribution</td>
<td>Appropriate vehicles; Loading and un/loading equipment; Containers.</td>
<td>Cold chain, a complete</td>
<td>Refrigerated transport; Suitable containers</td>
</tr>
<tr>
<td>4 Storage</td>
<td>Controlled humidity (dry conditions), ventilation; Protection against insects and rodents</td>
<td>Refrigerated and ventilated storages; Controlled humidity</td>
<td>Controlled atmosphere (low oxygen); Controlled (low) temperature facilities</td>
</tr>
</tbody>
</table>

*) For dried F&V - facilities, independent of the sun shine.


Possible technological improvements are gathered in Table E7; they are presented by groups of commodities and for each of four stages outlined in Table E1. In general, mechanisation of harvest and post-harvest handling is associated with commercialisation of farming and people moving out of agriculture. The reason for introducing mechanisation in the harvest of grains and root and tuber crops is mainly for managing quantity when yields improve and achieving greater efficiency including elimination of crop losses. However, it might also be essential for controlling maturity and quality of...
crops (e.g. killing vines of potatoes). For fruits and some vegetables, manual harvesting stays preferable. Mechanisation of postharvest handling and use of appropriate containers will have positive impact on the reduction of crop losses of roots and tubers, and FFV. Mechanisation of threshing and separation of the chaff from grains will also reduce losses. Low content of moisture is essential for preventing storage losses of grains; if there is wet weather during harvest, grains have to be dried, for which a technology independent of the sunshine is needed. In contrast, harvested fruits and vegetables must be cooled in order to slow down their respiration and transpiration otherwise leading to their biological deterioration. The mechanised harvest might cause breaking skins of root and tuber crops. These crops, however, have the ability to heal their skin wounds when held at relatively high temperatures and humidity for few days after harvest whilst at the same time there is a general strengthening of the skin. The term "curing" refers to the operation of self-healing of wounds, cuts and bruises (UCDAVIS 2013). Appropriate storage requires control of temperature, humidity and good ventilation; dry conditions for grains and low temperature and appropriate humidity for roots, tubers, fruits and vegetables for keeping the water content. Fruits and vegetables will benefit from storage technologies reducing the supply of oxygen (Kohli 2008).

Good transport infrastructure (roads, railways) allows bringing crops quickly from fields to storage places. Well equipped vehicles and the appropriate containers will assure that crops are not damaged or spilled during the transport.
While technological solutions are largely available it is not simple to bring them into practice (World Bank 2010; Hodges et al. 2010). Kitinoja et al. (2011) pointed out “... many technologies have been developed to reduce these losses, they have not been implemented, in many cases, due to one or more of the following socioeconomic factors: (1) inadequate marketing systems; (2) inadequate transportation modes; (3) unavailability of needed materials, tools, and/or equipment; (4) lack of information; and (5) governmental regulations and legislations.” Building on these and other authors like Rolle (2006) or Rangi (2010) we can elaborate a broader problem area which we mark as organisational and institutional: First, crop losses depend on a number of factors including those which are beyond the control of farmers; to address them simultaneously requires knowledge. Second, modernization of harvest and post-harvest technologies usually needs investment for which many farmers in developing countries have no resources. Causes can be that farms are too small and primarily produce for their own consumption (e.g. subsistence farms in Sub-Saharan Africa), or that the financial flow in the marketing system is inefficient (e.g. Kazakhstan). Third, (which links to the previous) farmers are not integrated in markets / there are many intermediaries and the system is largely inefficient; farmers cannot sell their produce, crops are stored for too long time and the losses are high. Fourth, infrastructure is poor and the government has no means or interest to invest in it. Fifth, as it has already been pointed out, often improving one operation in the FSC (e.g. introducing high yield varieties) requires adjustment /
improvement of the follow up activities of which farmers are not aware or do not have skill or financial means to address them. Both the technological and organisational/institutional solutions are illustrated in Figure E4.

Hodges et al. (2010) following World Bank (201) argues that the reduction of postharvest losses in least developed countries will need considerable investment to create more formal markets and improve their performance. Some of these improvements need to take the form of public ‘goods’ including infrastructure such as the development of networks of all-weather feeder roads so that crops can get to market, a problem especially acute in Africa where transport costs can be five times those in Asia (World Bank 2009). Developing market infrastructure and institutions (including rules and organisations of horizontal cooperation, fair contracts leading to vertical integration and credit supply) will enable farmers and post-harvest merchants to invest in better technologies and facilities. Collective marketing can take various forms and for grains may include inventory credit schemes and Warehouse Receipt Systems to accelerate the efficient removal of the crop from the farmer into safe centralized storage (Coulter, Shepherd 1995 cited in Hodges 2010). More rapid and comprehensive adoption of technical solutions (innovations) can be stimulated through innovations systems (including the financial side of it) and learning alliances (World Bank 2006). Low adoption (low level of innovation) might also rest in the differences of the scale; the technologies might be too costly for small farmers or even impossible to operate on small farms. There are two directions of solution: i) research and development of technologies for small farms or ii) cooperation of farmers – establishing a cooperative for harvest and postharvest operations. Plastic silo bags for storing grains under controlled atmosphere (Bartosik et al. 2008) can be an example of the first (i) solution.

Past experience shows that the support system cannot be exclusively technically focused (Parfitt 2010; Kitinoja et al. 2011); in contrary, more types of intervention are needed: “institutional” providing effective rules, knowledge transfer support, improved access to credits and often direct market intervention providing stabilisation through temporary storage of surpluses. In addition, producers must be guided to see a clear direct or indirect advantage, particularly financial benefit. Good examples of successful policies are countries like Brazil, India or Ukraine as it is indicated in Valdes et al. (2009), Reardon & Minten (2011), Striewe (2011 ). Both Brazil and India established special actions to address post-harvest losses: In India, it is the “All India Coordinated Research Project on Post-Harvest Technology”, which develops post-harvest technologies and support transfer of them to the farming practice. Brazilian Agricultural Research Corporation (Embrapa) provides information on main causes of harvest and post-harvest losses by crops and advises farmers how to avoid them.

The European Commission launched a project on monitoring harvest and postharvest losses in East and Southern Africa (APHLIS). The main objective of this project is to gather information on post-harvest losses in order to forecast food supply in poor African countries.
5. ASSESSMENT OF SELECTED FOOD SUPPLY CHAINS

In this chapter, the current stage of harvest and postharvest technologies in three food supply chains (FSC) – grains (cereals), fresh fruits and vegetables (FFV), and roots and tubers – is discussed. Particularly in the latter two FSC, variability of crops is high and also of cultivars within individual crops having many different properties requiring different postharvest treatment. However, the analysis concentrates on common postharvest treatment principles and methods in each commodity group showing only most important specific needs of some crops, because the study cannot go into details.

5.1 Grains

Harvest and post-harvest treatment grains include four steps

> Cutting cereal plats (Harvesting)
> Threshing/shelling, winnowing/cleaning: when grain is separated from the ear
> Drying (parboiling in the case of rice)
> Storing

Technologies vary across farming systems and regions. Two technological lines can distinguished:

1. Modern, which uses combine harvester unifying two first steps in one and also, fine cleaning and drying are usually integrated with storing. This technology is largely mechanised and demanding energy (electricity, fuel) for drying and handling. Grain is stored in bulks in metal or concrete silos. Scale of operations is large; farmers often cooperate horizontally and are fairly integrated with large grain merchants or processors (milling industry).

2. Traditional, in which all four steps are conducted separately. The share of manual work is high (thus mechanisation is low). In many parts of the world, manual harvesting, threshing, winnowing, open sun drying prevail on small farms. Semi-subsistence farmers store their grain in their farmhouse in sacks or bins. The food chain includes several rather small intermediaries storing crop temporarily before transported to mills or large grain elevators (public or private). For better handling, grain is transported and stored in bags.

In practice, there are various transitional forms. Often, the government or a governmental organisation is involved in grain logistic and storing for strategic food security reasons.

If managed well, the modern system produces very limited grain losses. The main losses due to spillage or mechanical damage of kernels can be attributed to handling and poor maintenance of combine harvesters, transport vehicles, transport belts or fans. Regular upgrading and good maintenance of machinery and equipment will assure low losses of this type.

Despite the improvements in agro-technology, particularly improvements of the effectiveness and availability of pesticides, harvested grain will still be threatened by biodegradation spoilage mainly due to moulds (e.g. Aspergillus, Penicillium and Fusarium). There is a special paragraph devoted to the issue of moulds and mycotoxin later in this section.

Generally, the main R&D stream in postharvest technology aims at reducing crop losses and labour input. Technologies are capital intensive, and in their scale usually suitable for well integrated cereal food chains with large farmers or farmers’ cooperatives and big intermediaries.

In contrast, high harvest and postharvest losses are immanent to poor small semi-subsistent farmers and small intermediaries. These small farmers rely on traditional technologies. Ranges of crop losses (as compiled from various sources, Table E8) are broad; the loss might be high at each postharvest treatment step. In countries, where small semi-subsistent agriculture dominates, the reduction of crop losses thus might be one of the keys for strengthening food security (e.g. South-east Africa, South Asia).
Table E8: The range of grain losses at each postharvest treatment step in developing countries

<table>
<thead>
<tr>
<th></th>
<th>Threshing</th>
<th>Drying</th>
<th>Parboiling (only rice)</th>
<th>On farm storage</th>
<th>Handling and transport</th>
<th>Central storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5-13%</td>
<td>1-5%</td>
<td>1-2%</td>
<td>1-15%</td>
<td>3-10%</td>
<td>1-6%</td>
</tr>
</tbody>
</table>

Source: Compilation from various authors: Henssel (2009), Hodges et al. (2010), Parfitt et al. (2010), Rembold et al. (2011).

5.1.1. Threshing

The traditional threshing of cereals includes a number of methods (FAO 1994; IRRI 2013):

- by hand when bunches of panicles of rice, wheat, barley, etc. are beaten against a hard element (e.g., a wooden bar, bamboo table or stone) or with a flail. In the case of maize, kernels are separated from the cob by pressing on the grains with the thumbs. In the case of millet, the grain is separated from the ears with a mortar and pestle;
- trampling, when the crop is threshed by being trodden underfoot (by humans or animals)
- using a vehicle circulating over cereal bunches as these are thrown on to the threshing area.

The traditional cleaning method is winnowing, which uses the wind to remove light elements from the grain.

Table E9: A comparison of threshing methods

<table>
<thead>
<tr>
<th>Method</th>
<th>by hand</th>
<th>by foot</th>
<th>using vehicles</th>
<th>mechanised (modern)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>10.30</td>
<td>30-50</td>
<td>a few hundreds of kilograms</td>
<td>300-2000</td>
</tr>
<tr>
<td>Nature of losses</td>
<td>unthreshed grains, lost kernels around the threshing area (when harvested too late), losses 1-4%</td>
<td>broken kernels or buried in the soil</td>
<td>broken kernels (&lt;3% for rice, &lt;0.7 for other cereals), affected by grain moisture. Threshing rate &gt;99%</td>
<td></td>
</tr>
</tbody>
</table>

Source: FAO (1994), various internet sources

The traditional ways of threshing and winnowing are gradually replaced by mechanisation; there is a great contribution of international research centres like International Rice Research Institute (IRRI), International Maize and Wheat Improvement Center (CIMMYT), French CIRAD etc. to the development of threshing and cleaning engine powered equipment suitable for small farmers in developing countries. Simple design, easy handling and versatility (maize, millet, sorghum, etc.) are necessary preconditions for a successful adoption of these mechanisations. The great efficiency of the mechanisation attracts interest of farmers even in countries where labour is cheap and abundant (Ethiopian ATA 2013). In many
cases, saving time is the main motivation for adopting mechanised threshing and cleaning on small farms where these operations are usually done by the farmer or his spouse themselves. Another motivation (particularly for using a grain cleaning machine) is increasing requirement of quality standard when grain is sold on the market (FAO 1994).

Even if chosen the small one, the modern threshing and cleaning equipment will often greatly exceed the needs of individual farmers in developing countries. Unless the equipment is shared among other farmers (either on a cooperative or commercial base), the spread of the technology is limited; particularly when taking into account cost of $1000-$2000. Sharing the threshing equipment requires planning harvest and substantial level of social capital.

The efficiency, quality and level of losses vary greatly not only across the above technologies but also due to various input and operational factors: While some new high yield varieties might be difficult for traditional threshing and shelling (FAO 1994), to achieve significant improvements in terms of reducing crop losses, operators of modern threshing machines must check humidity of input crop, select the appropriate beater and control drum speed of the thresher. Alizadeh and Khodabakhshipour (2010) showed that the drum speed of the axial flow thresher and paddy moisture content had significant effect on the broken and cracked grains. Asgha et al. (2004) found that the wheat losses due to broken and cracked kernels might change by 40% during the day – which phenomenon is associated with varying moisture content due to varying humidity over a day. Peksen et al 2013 showed significant threshing rate differences between various beater forms of threshers. It implies that progress in threshing technology must include beside a new machinery also devices for checking parameters of harvested crop and knowledge of those who operate this machinery how to control the threshing process. As we will see later, this conclusion holds for all advancements in postharvest technology.

5.1.2. Drying

We showed in the last paragraph that moisture content is important for mechanical threshing. However, moisture content is even more important for storing, since high moisture content encourages fungal and insect problems, respiration and germination. Moisture content in the growing crop starts to decrease as the crop reaches maturity. If weather is wet during harvest or the crop is harvested before the moisture level of grains drops to the required level, the grain must be dried.

The simplest traditional method is sunshine thin-layer drying on an open platform or a simple maize crib. On the other pole is a continuous-flow (fuel heated) dryer, usually integrated within the large (central) grain storage.

The losses are usually low regardless which system is used; grain is lost due to spillage and exceptionally also if the grain moisture drops too much that it increases kernels propensity to crash. Thus the issue from the point of view of reducing crop losses is the choice of effective drying equipment with an effective moisture control system.

Drying systems fall into two main groups:

> Natural drying using ambient air temperature and either direct sunlight or natural air movement through the crop in shallow layers.

> Artificial drying using powered movement of air through the crop either at ambient temperature or fuel heated.

The choice is governed by a number of factors: First of all, the natural system can only be used if it is able to reduce moisture to the required storage level. The same must hold when designing the artificial drying system. Second, the capacity of the system must be able to keep pace with the rate at which the

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4 This is also of concern of various information and knowledge webs, e.g. IRRI (2013)
grain arrives at the store on a daily basis. It is essential that loading and drying does not hold up the harvest. Third, both capital cost and running cost should be taken into account.

It is obvious, that natural system can hardly be used for large grain quantities like those which are delivered at large scale storages. Nevertheless, the recent development of solar energy technology enables farmers or storage providers to use efficient solar convertors (either heating water or air) as heating units (Agriculture Solar 2013).

There are some simple methods for assessing if the moisture content dropped to its required level, which perform relatively well (e.g. the salt-jar method, FAO 1994). Nowadays, there is a good offer of handheld grain moisture meters on the market; the price ranges from $150 to $800. (Professional Equipment 2013)

5.1.3. Storing grains

Continuous consumption and seasonal production (maximum 2 harvests a year, but mostly only one) of grains makes necessary to store them. Beside food store, a part of the harvest must be stored as seeds for future sowing. Seeds require a bit different storage conditions than grains for human or animal consumption. In the developed countries, production and marketing of seeds has separated from the production for consumption, while in many developing countries the common practice is to save part of the harvest for future reproduction. With the new hybrid or GM crop varieties own reproduction of seeds has declined in general.

We can distinguish two types of grain storing by their location on farm and outside the farm (Figure E5). Farmers store the harvest on their farms for own consumption including household consumption and animal feeding. Farm storage also provides a form of saving, to cover future cash need through sale, or for barter exchange or gift-giving. Often, grain is kept on the farm awaiting better price later.

Large farmers usually deliver their gain to central elevators by themselves, while small farmers rely on intermediaries; in developing countries these are usually small traders who keep grain temporarily, before deliver it also to large merchants or governmental storages or to processors.

The losses (which might be considerably high) depend on the technology and people who manage it, particularly how these two factors protect the grain against being eaten by rodents or insects or biodeteriorated.
The storage technology rests on good protection against an invasion of rodents and insects and in controlling temperature, moisture and possibly oxygen supply that insect and fungal pests cannot develop.

The modern grain storage technology uses metal or concrete silos which can be perfectly sealed as well as well ventilated if needed. Drying unit is usually part of the storage system. Grain is stored in bulks and the loading and unloading processes are fully mechanised. Moisture and temperature inside the silos is monitored continuously and the system is designed in the way that corrective actions can be taken if needed. However, such technology is investment intensive. Also, the storage capacity is high (although smaller metal bins are also available, see later). Therefore, only large crop farmers or animal farmers if they need to store a lot of grain for animal feeding through the year invest in such a technology. Huge central grain elevators are usually built by cereal merchants, processors and governmental bodies. In spite of high investment costs, the cost of grain storage (including drying) per tonne per year is about US$7 - US$14 i.e. about 2-4% of the current wheat price\(^5\) (ISU 2013).

In South America, North America, Ukraine or Russia large scale farmers use large hermetic plastic bags (silo-bags) for storing grain. The plastic cover is made of three layers (white outside and black inside) with 235 micrometers of thickness. These silo-bags can hold approximately 200 tonnes of wheat and with the available handling equipment it is quite simple to load and unload them. While silo bags provide easy and cheap on farm grain storage (up to 12 months, Bartosik et al. 2008), there might be a problem with the disposal of used bags. The problem is that until recently there were no many businesses interested in collecting silo-bags for recycling and that the bag must be cut to better manageable pieces before brought to a collection point (Holmes, Springman 2009).

Source: Own illustration

\(^5\) In the past before price soaring, it was about 5-10% of the price.)
Medium size farmers, groups of farmers (in a village) or smaller intermediaries tend to use warehouses where grain is stored in sacks or bulks. Indian godowns might be an example of it. The godowns are “scientific” storages since they should provide storage practices (including fumigation, monitoring of temperature and humidity, etc.) according to the scientific guidelines. The godowns are private or public warehouses integrated in the Food Corporation India.

Small farmers in developing countries use traditional storage systems and their improvements. Quite a rich list of storage facilities for small farmers in developing countries is presented in FAO (1994) or in Hayma (2003). The list of more traditional technologies include jute sacks (which have to be however stored on water proofed platform with a protection against rodents and covered against rain), clay pots, maize cob crib, earthen silo, Burkina silo made of bricks or metal drums usually concerted water or oil tanks.

Problem of the traditional storage technologies is that they provide rather poor protection against insects and water. Improvements include plastic sacks which can be hermetic sealed. The plastic is waterproofed and tight enough that it provides protection against insects. Another example of an improved technology is the Indian Pusa bin; it is a square silo, double-walled all the way round (including the floor and roof) with a separating layer of plastic sheet between the walls. The plastic protects against moisture and keeps air from entering the stored product, provided the fill- and outflow openings can be tightly closed. The walls are usually made of mud blocks (sometimes mixed with cement). It gives good protection against insects and rodents, especially if the bottom 50 cm of the outside walls and the bottom layer are made of fired bricks or concrete. (Hayma 2003).

In spite of being considered as expensive, small metal silos were successfully introduces in many places (Anon 1982; Walker 1975; Breth 1976). Often, these were built for the use of farmers from a village. However, in many places there is no sufficient social capital for collective action (e.g. ADBI, 2013) and farm-level storage must continue on individual base. EGSPI (2008-2011), EGSP-II (2012-2016) projects aim to improve grain storage of poor farmers, particularly women farmers, in eastern and southern Africa, through the dissemination of small metal silos which can be kept in framer’s house.

The successful storage rests on the following pillars (FAO 1994, Hayma 2003):

1. Grain is properly dried, it is clean of broken and crushed kernels (these are more susceptible to mould infestation). Grain should be healthy, if needed, pesticides or fumigation of stored crop is applied (e.g. aluminium phosphate).

2. The storage provides firm protection against insects and rodents.

3. Internal temperature and humidity is maintained stable and low

4. There is a procedure how to homogenise stored crop that there are no humid spots.

In addition, a certain degree of gas-tightness provides protection against development of insects and fungi). It is, because respiration of the biotic components of the grain mass increases carbon-dioxide and reduces oxygen concentrations. The dropping concentration of oxygen limits grain respiration and mould and insect development. It has also been also observed that high carbon-dioxide concentration reduced the ability of Aspergillus flavus to produce aflatoxin (Rodriguez et al. 2008).

We have indicated that traditional technologies do not provide sufficient protection of stored crops and therefore, the losses are high. On the other hand, good technologies are available and there is increasing offer of such which in their scale fits to the needs of small farmers. Changing storage technology depends on many factors. Subsistence farmers (who have very limited cash) will always find buying storage equipment as less favourable than making it from a variety of locally available materials like paddy straw, wheat straw, wood, bamboo, reeds, mud, bricks, cow dung etc. Farmers might lack

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6 Alternatively, hermetic plastic bags are provided.
knowledge and confidence that new technology will really reduce losses significantly. Also, it is not only the storage sack/bin/silo which will solve the problem of crop losses. It will also require management and additional knowledge. The farmer must assure that the moisture content of grain is sufficiently low, that grain put in the storage place is clean and healthy. Disinfection of the storage place might be required. Small commercial farmers might need more flexible storage facility since the harvest vary from year to year and also the time the grain is kept on the farm before selling might be highly variable. Thus these farmers will be reluctant to invest in a technology which might provide good and save long term storage but for high (investment) cost. As we have already mentioned shared warehouses or silos (at village level or in a cooperative of producers) might be an option, but there must be a commitment of all farmers to assure quality and safety standards of their crops put in the joint storage. In addition, sufficient social capital for a collective action is needed.

Another option is to bring harvested grain as soon as possible to the large modern storages (central storages). India represents rather successful case in this respect (e.g, Naik, Kaushic 2011). Price guarantee makes the flow of grain to storages easy. Moreover, the participating agencies provide cleaning, handling and transportation, procurement and distribution, disinfection services, fumigation services and other ancillary activities ie safety and security, insurance, standardization and documentation (India Agronet 2009). The weakness of the Indian system is (according to Singh 2010) that (a) it is entirely oriented on food security of urban areas, while rural areas, and in particular very small farmers, might be short in grain (b) in order to cope with increasing production (stimulated by governmental subsidies – price guarantee) the godowns do not conduct according to the recommended (“scientific”) practices and a lot of grain is spoiled.

International development assistance programmes tend to support 'modern' capital-intensive systems (Coulter 1991): silos/elevators against warehouse or bulks against sacks. There are however warning cases that such investment plans paid little attention to local conditions resulting in low or no effect (eg. Pakistan: Coulter 1991; or Millig Corporation of Tanzania: FAO 1994).

5.1.4. Mycotoxin

Mycotoxins are the cause of a range of human and/or animal diseases and occur in a variety of grains. The ingestion of mycotoxins can produce both acute (short-term) and chronic (medium/long-term) toxicities ranging from death to chronic interferences with the function of the central nervous, cardiovascular and pulmonary systems, and of the alimentary tract. Some mycotoxins are carcinogenic, mutagenic, teratogenic and immunosuppressive. Aflatoxin B., for example, is one of the most potent hepatocarcinogens known. The main characteristics of the most severe mycotoxins are given in Table E10.

According to the site and time of infestation, the fungi can be divided into three groups: (a) Field fungi (b) Storage fungi (c) Advanced deterioration fungi (Gowda et al. 2013). Fusarium is a typical field fungi. The storage fungi are Aspergillus and Penicillium. The advanced deterioration fungi, normally do not infest intact grains but easily attack damaged grains and requires high moisture content, that include Aspergillus clavatus, Aspergillus fumigatus

The pre-harvest control of the fungal agents is limited by our inability to control the weather. Both insufficient and excessive rainfall during critical phases of crop development can, lead to mould contamination and mycotoxin production. The very serious health consequences and the substantial economic losses attributed to mycotoxins (over $1 billion losses to agricultural industries in Canada, Xue 2013) clearly emphasize the need for research and development in the area of the prevention of mycotoxin contamination worldwide.
A considerable effort has been expended on the development of crop strains which are resistant to mould growth and/or mycotoxin production. FAO (1994) was quite optimistic in respect to attempts to exploit the resistance to mycotoxin production (through either the inhibition of synthesis or chemical degradation) because of the limited number of genes which control this process. However, fifteen years later, researchers (e.g. Abbas et al. (2009), Xue (2012)) are much more careful in expectations, stressing that resistance breeding has not been productive yet, and cultivars with high levels of resistance are not yet commercially available. In contrast, Xue (2012) is enthusiastic on bioagent as ACM941 (a strain of Clonostachys rosea) with lab and field test effects of about 50% reduction of mycotoxins. Similarly, McClure (2012) published on its web good experience with bioagent based AflaGuard eliminating the development of aflatoxin. Bioagents are nontoxic strains of funguses applied to the field in a large enough quantity mid-season so that it outcompetes the toxic ones. Many authors like Alakonya and Monda (2013) emphasize good agricultural practices (including crop rotation, management of crop residues, and timing) as an effective instrument in reducing fungus infestation. Ma et al. (2013) shows

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Table E10: Main mycotoxins: production and effects

<table>
<thead>
<tr>
<th>Fungus</th>
<th>Aflatoxin</th>
<th>Trichothecenes (T-2)</th>
<th>Deoxynivalenol (DON)</th>
<th>Zearalenone</th>
<th>Fumonisins FB1 and FB2</th>
<th>Ochratoxin A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspergillus flavus and Aspergillus parasiticus</td>
<td>Fusarium sporotrichoides</td>
<td>Fusarium graminearum</td>
<td>Fusarium graminearum</td>
<td>Fusarium moniliforme</td>
<td>Penicillium verrucosum Aspergillus ochraceus</td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>cereals (maize in particular)</td>
<td>cereals (wheat, rye)</td>
<td>cereals (wheat and maize)</td>
<td>cereals (wheat and maize)</td>
<td>cereals (maize in particular)</td>
<td></td>
</tr>
<tr>
<td>Climate/weather</td>
<td>tropical, sub-tropical</td>
<td>tempered, cold</td>
<td>worldwide</td>
<td>worldwide</td>
<td>worldwide</td>
<td></td>
</tr>
<tr>
<td>Other contributing factors</td>
<td>broken, damaged kernels</td>
<td>if the crop stays on the field over winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Health effects on humans</td>
<td>hepatocarcinogenic, retard growth of children</td>
<td>Immunosuppressive activity, 'alimentary toxic aleukia' (ATA).</td>
<td>immuno-suppressive effect</td>
<td>toxic</td>
<td>toxic</td>
<td></td>
</tr>
<tr>
<td>Health effects on animals</td>
<td>through feed transmitted to milk</td>
<td>emetic and feed refusal syndromes</td>
<td>oestrogenic syndromes</td>
<td>leukemia</td>
<td>renal toxicity, nephropathy and immuno-suppression</td>
<td></td>
</tr>
<tr>
<td>Concentration limits</td>
<td>0-50 ppb</td>
<td>1 ppm</td>
<td>not established</td>
<td>4 ppb</td>
<td>not established</td>
<td></td>
</tr>
</tbody>
</table>

Note: $ppm = \frac{mg \ of \ solute}{kg \ solution}$, $ppb = \frac{\mu g \ of \ solute}{kg \ solution}$

Source: Murphy et al. (2006), FAO (1994)

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7 Some tests toward development of commercial cultivars have already started: for example see [http://www.ars.usda.gov/is/pr/2010/100520.htm](http://www.ars.usda.gov/is/pr/2010/100520.htm)

8 Offered by Syngenta - the product is actually a form of Aspergillus flavus that is benign.
that better agronomic practices might importantly reduce Fusarium graminearum and deoxynivalenol (DON) concentrations in spring wheat.

Alakonya and Monda (2013) believe that biological protection based on bioagents outcompetening the dangerous funguses can be a pervasive solution for African countries: they suggest (i) selecting local non-toxigenic strains and registering them for mycotoxin management (ii) launching extensive education programmes to raise awareness of (small) farmers and intermediaries; (iii) content of mycotoxins (effectiveness of the measures) should be monitored; (iv) government should provide incentives for farmers, particularly the small ones, to adopt biological protection measures.

The postharvest handling of grains does, however, present another opportunity for controlling mycotoxin production. First of all, reducing the moisture of grains and lowering temperature as far as possible will, as it was pointed earlier in this study, reduce both, the spread of funguses and the production mycotoxin. Fungal growth can also be inhibited by chemical methods as application of fungicides and fumigation with ammonia or ozone. In recent years, phytochemicals (i.e. antifungal plant extracts) are explored for controlling fungal diseases as an alternative to synthetic chemicals (Anjorin et al. 2013).

Second, the identification and segregation of contaminated material is necessary. It should be pursued through the implementation of quality control procedures on farm and at the delivery in the storage. Automatic colour sorting, often in combination with manual sorting, is widely used to segregate kernels of abnormal appearance as well as in processing.

Finally, the most recent methods concentrate on the microbiological destruction (detoxification) of the mycotoxin(s). Fernandes Oliviera et al. (2013) reports positive effects of decontamination of aflatoxin by Lactic Acid Bacteria and yeast (Saccharomyces cerevisiae). This is, however, a method applied in processing.

The above mentioned approaches to the mycotoxin problem in grain production and storage are summarised in Table E11.
An essential step in combating mycotoxin is the identification of the problem. First, it is important to state norms (acceptance levels) of mycotoxin concentration in grains and second to measure it. FAO conducted a survey on mycotoxin regulation in 2002-2003 (FAO 2004). On a worldwide basis, at least 99 countries had mycotoxin regulations for food and/or feed in 2003 which represents an increase of approximately 30% compared to 1995. The total population in these countries represents approximately 87% of the world’s inhabitants. The most dissatisfactory situation was in Africa, only 15 countries had mycotoxin regulations, representing 59% of African population. However, the limits vary substantially, for aflatoxin from zero to 50 ppb (Mahuku and Silla 2011; FAO 1994).

Measuring mycotoxin contamination of grains requires both good sampling method and good analytical method. Sampling is an issue because the distribution of funguses and mycotoxins is highly skewed in grains (FAO 1994). Laboratory high performance liquid chromatography (HPLC) has been used for the analysis of a wide range of mycotoxins including the aflatoxins, ochratoxin A, zearalenone, deoxynivalenol (DON) and the fumonisins. However, simple, rapid, efficient screening methods which can be handled by relatively unskilled operators are needed for practical use on small farms or by small traders in developing countries (Coker 1991)9.

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9 Current mycotoxin screening tests kits cost between $180-$400 (SeedBuro 2013). It means, the instrument is too expensive to be used on small farms or at the village level cooperative.

Table EI1: Mycotoxin management in grains

<table>
<thead>
<tr>
<th>Stages Methods</th>
<th>Physical methods</th>
<th>Chemical methods</th>
<th>Micro-biological methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-harvest (production phase)</td>
<td>Crop rotation; selection of more resistant varieties</td>
<td>Using fungicides</td>
<td>Development of resistant varieties; application. Biological control using competing, non-toxic strains of funguses</td>
</tr>
<tr>
<td>Harvest</td>
<td>Appropriate timing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postharvest operations</td>
<td>Using threshing methods not damaging kernels; segregation of infected grains, broken grains, and husks; drying grain to the safe moisture level</td>
<td>Fumigation (amonia); ozonization</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>Admitting only safe crop, keeping temperature low and maintaining the appropriate moisture content; using sealed storage bins.</td>
<td>Acids, bases (amonia), oxidants, bisulphites, chlorinated agents, etc. not well accepted by consumers.</td>
<td>Using yeast (Saccharomyces cerevisiae) and lactic acid bacteria (LAB)</td>
</tr>
<tr>
<td>Processing</td>
<td>Segregation of contaminated grains; in animal feeding: dilution of the contaminated feed with safe feed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Various sources referred in the previous text.
Figure E6 summarises the above methods for dealing with mycotoxins from the point of view of the research and application intensity. While biotechnological solutions are not ready for practical application (perhaps more resources are needed to be put into research and knowledge transfer) conservative and chemical methods needs more training and encouragement for their adoption.

Figure E6: Main scientific streams of dealing with mycotoxins

<table>
<thead>
<tr>
<th>Research</th>
<th>Development of resistant varieties; Biological control using competing, non-toxic strains of funguses</th>
<th>Chemical inhibitors; Conservative methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge transfer to commercial products</td>
<td>too early, partly Corn; Aflasguard, generally awaiting</td>
<td>Abamia fumigation, ozonization; pre- and postharvest management, equipment (threshers, dryers, storage facilities)</td>
</tr>
<tr>
<td>Training</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Blue intensity relates to the intensity of the activities; for BT corn effect on mycotoxins see Wu (2006)
Source: Own illustration

5.2. Fresh Fruits and Vegetables

In contrast to grains and roots and tubers, fruits and vegetables cannot be considered as staple food, perhaps except green bananas (plantains) which provide an important source of starch in tropical regions. Nevertheless, fruits and vegetables are important sources of essential minerals and vitamins in the human diet. When eaten together with some root crops (potato, sweet potato) they provide a proportion of protein requirements as well as variety in flavour and colour (FAO 1989). Most of fruits and vegetables are highly perishable, which contributes to high losses (already mentioned in the first part). Mango postharvest losses in several tropical countries (Benin, Brazil, Costa Rica, Pakistan) range between 15% in the dry season and 80% in the rainy season mostly due to poor storage and anthracnose (Kitinoja 2010, Kader 2009).
Figure E7: The cold chain scheme

Some fruit and vegetable produce is immediately processed (canned, pickled, frozen)\(^\text{10}\); in this case there is very little space for postharvest losses. There are four main causes of postharvest losses in the area of fresh fruits and vegetables (FFV) (FAO 1989; Gross et al. 2004):

1. It is typical for fruits and vegetables that biological processes like ripening continue after harvest at relatively high speed. Thus crop spoils if it is not consumed immediately;
2. Mechanical damage during harvest, transport and handing, damaged crop might be more prone to pests (e.g. mould attack);
3. Bacterial and fungal infestation during the late vegetation period or harvest handling causing consequent spoilage. The propensity of some crops (e.g. strawberries or mango) to this type of spoilage is particularly high;
4. Storage linked damages (chilling or freezing injuries, too high CO\(_2\) concentration, etc.)

\(^{10}\) Dried fruits are usually added to fresh produce.
### Table E12: Storage parameters of selected fruits

<table>
<thead>
<tr>
<th>Fruit</th>
<th>Pre-storage treatment</th>
<th>Curing</th>
<th>Storage atmosphere</th>
<th>Storage temperature °C</th>
<th>Relative humidity</th>
<th>Storage period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strawberries</td>
<td>forced air cooling, (1h after harvest)</td>
<td>-</td>
<td>MAP (10-30% CO2)</td>
<td>0</td>
<td>90-95%</td>
<td>7 days</td>
</tr>
<tr>
<td>Cherries</td>
<td>hydro- or forced air cooling</td>
<td></td>
<td>CA and MAP</td>
<td>-1 to 0</td>
<td>&gt;95%</td>
<td>2-4 weeks</td>
</tr>
<tr>
<td>Apple</td>
<td>room cooling, forced-air cooling</td>
<td>RA</td>
<td>RA</td>
<td>-1 to 4</td>
<td>90-95%</td>
<td>up to 4 months</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CA (ULO)</td>
<td>0-2</td>
<td>90-95%</td>
<td>up to 12 months</td>
</tr>
<tr>
<td>Oranges</td>
<td>room cooling, hydro- or forced-air cooling</td>
<td>RA</td>
<td>RA</td>
<td>0-1</td>
<td>85-90%</td>
<td>12 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3-8</td>
<td>90-95%</td>
<td></td>
</tr>
<tr>
<td>Mango</td>
<td>room cooling, forced-air cooling</td>
<td>to be kept at higher temperature for a day</td>
<td>RA</td>
<td>10-13</td>
<td>85-90%</td>
<td>up to 3 weeks</td>
</tr>
<tr>
<td>Banana</td>
<td>No</td>
<td></td>
<td>CA (2.5% O2 and 2.5% CO2)</td>
<td>13.3-14.4</td>
<td>90-95%</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** RA = Regular Atmosphere, CA = Controlled Atmosphere, ULO = Ultra Low Oxygen, MAP = Modified Atmosphere Packaging

Source: Gross et al. (2004)

### 5.2.1. Current technology (cold chain)

Technologies to address the first three causes include: (a) appropriate chemical and biological protection of crops at field/ orchard before harvesting; (b) timely harvest, using appropriate harvest methods based on manual picking-up, choosing appropriate and clean containers and the discipline of worker harvesting the crop; (c) cooling down the crop often together with controlling availability of oxygen in order to slow down ripening and other biological processes, (d) appropriate packaging and (e) careful, refrigerated and timely transport. Actually, these points (a) to (e) more or less represent stages in a sequential process of FFV production and distribution which is called cold chain Figure E7). Failure at
the preceding stage will almost inevitably cause losses in the following steps. During the process, high hygiene standards must be fulfilled.

In contrast, the fourth type of damage results from the effort to prolong the storage life of crops by applying the cold chain technology. It includes chilling and freezing injuries, CO\textsubscript{2} injuries, etc. (see later).

**Table E13: Storage parameters of selected vegetables**

<table>
<thead>
<tr>
<th>Pre-storage treatment</th>
<th>Storage</th>
<th>Pre-cooling</th>
<th>Washing</th>
<th>atmosph.</th>
<th>temper. C</th>
<th>relative humidity</th>
<th>period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lettuce</td>
<td></td>
<td>vacuum cooling</td>
<td>-</td>
<td>RA</td>
<td>0</td>
<td>90-95%</td>
<td>3 weeks</td>
</tr>
<tr>
<td>Tomato</td>
<td></td>
<td>hydro- or forced air cooling</td>
<td>-</td>
<td>RA</td>
<td>&gt;10</td>
<td>90-95%</td>
<td>2 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CA</td>
<td></td>
<td>90-95%</td>
<td>6 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1-3% O\textsubscript{2})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snap and long beans</td>
<td></td>
<td>hydro- or forced air cooling</td>
<td>-</td>
<td>RA (CA)</td>
<td>0</td>
<td>95-100%</td>
<td>3 weeks</td>
</tr>
<tr>
<td>Cauliflower</td>
<td></td>
<td>RA</td>
<td>-</td>
<td>95-100%</td>
<td>3 weeks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cabbage</td>
<td></td>
<td>CA</td>
<td>-</td>
<td>98-100%</td>
<td>6 months</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunched green onion</td>
<td></td>
<td>hydro-, forced air - or vacuum cooling</td>
<td>-</td>
<td>RA/CA</td>
<td>0</td>
<td>98-100%</td>
<td>4 weeks (8 if CA)</td>
</tr>
<tr>
<td>Dry onion</td>
<td></td>
<td>room or forced air cooling</td>
<td>-</td>
<td>RA</td>
<td>0</td>
<td>98-100%</td>
<td>up to 9 months</td>
</tr>
<tr>
<td>Carrot</td>
<td></td>
<td>Hydro-cooling</td>
<td>water with chlorine</td>
<td>RA</td>
<td>0-1</td>
<td>98-100%</td>
<td>6 months</td>
</tr>
</tbody>
</table>

Notes: RA – Regular Atmosphere, CA – Controlled Atmosphere, ULO – Ultra Low Oxygen, MAP – Modified Atmosphere Packaging
Source: Gross et al. (2004)

It is obvious from Table E12 and Table E13 that the cold chain technology includes many attributes which must be adjusted to individual crops, because various fruits and vegetables are differently sensitive to these parameters (relative humidity, temperature, atmosphere composition etc.). It holds not only between crops, but also it concerns crop varieties.
Produce is usually cooled to its long-term\textsuperscript{11} storage temperature in special facilities designed to rapidly remove produce heat. Gross et al. 2004 present four (pre-)cooling technologies: (1) Forced-air cooling is the most widely adaptable method and is commonly used for many fruits and fruit-type vegetables; (2) Hydro-cooling uses water as the cooling medium and is less widely used than forced-air cooling because some products do not tolerate water contact, and it requires the use of water-resistant packaging; (3) Vacuum-cooling is usually applied to leafy vegetables that release water vapour rapidly allowing them to be quickly cooled. Sometimes, clean water is sprinkled on the crop (heads of lettuce) prior to carton closure to aid cooling if it is dry and warmer than 25 °C; (4) Room cooling is accomplished by placing warm produce in a refrigerated room. Cooling times are long, at least 24 h. It is used for a few commodities, such as citrus or onion. The need or extent of pre-cooling can be significantly reduced if the crop is collected early morning, or if it stays in the open air overnight.

Transport cooling in refrigerated ships and containers is used for products in areas with no cooling infrastructure, such as bananas. Highway trailers have insufficient airflow to cool produce and should never be depended on for initial cooling. Package icing utilizes crushed ice to cool and maintain product temperature and is used for a very few commodities, mainly for those whose purchasers have a strong traditional demand for this method.

We can distinguish two modes of storage atmosphere: regular air (RA) and controlled atmosphere (CA). CA storage involves reducing oxygen and increasing carbon dioxide in the air composition (O\textsubscript{2} from 21\% to less than 8\%, CO\textsubscript{2} from 0.03\% to values ranging between 1\% and 3\%) in order to inhibit the ripening process. Atmospheric modification should be considered as a supplement to maintenance of optimum ranges of temperature and RH. Exposure of fresh horticultural crops to low O\textsubscript{2} and/or elevated CO\textsubscript{2} atmospheres (within the range tolerated by each commodity) reduces their respiration and ethylene production rates (Gross et al. 2004). Storage under 1-3\% O\textsubscript{2} is referred to as Ultra Low Oxygen (ULO) storage. ULO is used for the long-term storage of apples, pears, blue berries and kiwis. In general, the lower the oxygen concentration, the longer the fruit can be stored. There is, however, a lower limit in terms of oxygen concentration, at which point fermentation will commence; this can reduce the quality of the fruit (and its shelf life, as a result). This is why ULO storage keeps O\textsubscript{2} concentrations over 1\%. Dynamic CA storage allows going below 1\% O\textsubscript{2} concentration being constantly adjusted on the basis of the fruit’s respiratory activity. Oxygen will be immediately amended if it too the currently low concentration starts to threaten crop quality.

Similar principle is applied in the Modified Atmosphere Packaging (MAP). This type of packaging reduces transmission of gasses between the inner and outer atmosphere, thus the concentration of O\textsubscript{2} decreases and the concentration of CO\textsubscript{2} increases which in turn limits ripening. MAP is applied to leaf vegetables like lettuce or spinach (Danish Technological Institute, 2008).

Alternatively, chemicals can be used to delay in ripening (My Agriculture Information Bank 2011): for example Kinins and Kinetins delay chlorophyll degradation of leafy vegetables, spinach peppers, beans, cucumber and others - in the effect, yellowing is retarded; Postharvest treatment of Gibberellins (GA) markedly retards ripening of tomatoes, guava and banana, while pre-harvest sprays of GA were shown to have a striking effect in decreasing the rate of development, maturation ripening of Kaki fruits and lemons and navel oranges because fruit will remain on the tree beyond normal maturity; Growth retardants might inhibit storage sprouting of onions, turnips, carrot and potatoes. A productive method of inhibiting fruit ripening is to inhibit ethylene perception. This can be done by gassing the molecules with 1-methylcyclopropene (1-MCP)\textsuperscript{12}, which binds tightly to the ethylene receptor and blocking the effects of ethylene (competitive antagonist).

\textsuperscript{11} Here, long term refers to a great range of periods: from several days needed basically to bring the production to urban areas or export markets to more than six months to allow a continuous supply on the market.

\textsuperscript{12} 1-MCP is sold commercially as SmartFresh and is approved and accepted for use in more than 34 countries (including the EU and US).
CA can have a direct or indirect effect on postharvest pathogens (bacteria and mould) and consequently on crop decay. For example, CO$_2$ at 10 to 15% significantly inhibit development of botrytis rot on strawberries, cherries, and other perishables. Low O$_2$ (below 1%) and/or elevated CO$_2$ (40 to 60%) can be a useful tool for insect control; similarly as in the case of grains (see the part on reducing postharvest losses in grains). Since high concentrations of CO$_2$ and low concentrations of O$_2$ can damage the crop, sanitary atmosphere alternations can be done for only a short period (Gross et al. 2004).

5.2.2. Modern storage technology induced disorders

It is obvious from what was said above that cold chain technology requires achieving and maintaining appropriate storage temperature, humidity and atmosphere and that different crops are differently sensitive to their values (Gross et al., 2004). Exceeding the range of safe values the stored crop will be injured (chilling, freezing injury, high CO$_2$ injury, too low oxygen concentration). Too rapid chilling or long exposition to chilling stress leads to tissue weakening, biochemical alterations and cellular dysfunctions. Often, injured products that are chilled will still look sound when remaining in low temperatures; symptoms of chilling injury become evident in a short time after they are removed to warmer temperatures. Commodities that are not susceptible to chilling injury are stored at as temperature slightly above the freezing point. However, cultivars, locations, and growing conditions may affect the actual freezing point of the stored crop. Also placing the crop to the entry of cold air in the storage can contribute to freezing injury. The most common symptom of freezing injury is a water soaked appearance. Too low concentrations of O$_2$ and high concentrations of CO$_2$ to certain physiological disorders such as internal browning in apples and pears, irregular ripening of fruits, such as banana, mango, pear, and tomato, development of off-flavors and increased susceptibility to decay (Gross et al., 2004, ).

Another disorder linked to long term storage is scald (apples, pears). Scald is an expression of damage and death within the surface layers of cells i.e. in fruit skin. It never occurs on the tree, only after relatively long periods of storage. Early in storage fruit accumulate a chemical called alpha-farnesene; being a volatile compound, much of it can evaporate from the fruit. As storage time lengthens the alpha-farnesene is oxidized to a group of toxic compounds called conjugated trienes, which do not evaporate and continue to accumulate as long as the fruit are kept in storage. Some cultivars are more susceptible to scald, immature fruits are more susceptible; hot weather in the late growing period contributes to the excessive development of alpha-farnesene. (Postharvest Information Network 2010).

5.2.3. Fungi and Mycotoxins

Fungi belonging to the genera Aspergillus, Pencillium and Alternaria are major contributors to fruit spoilage and are responsible for significant financial losses for any segment of the food industry that harvests, stores, processes or uses fruits or fruit-derived ingredients. Mycotoxins which are secondary metabolites produced by field/orchard or storage fungi represent serious health threats to humans. The main mycotoxins, fungi which are responsible for them as well as crop hosts are listed in Table E14.
Table E14: Mycotoxins in fruits and vegetables

<table>
<thead>
<tr>
<th>Mycotoxin</th>
<th>Fungus</th>
<th>Crops</th>
<th>Climate/weather</th>
<th>Other contributing factors</th>
<th>Health effects on humans</th>
<th>Concentration limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aflatoxin</td>
<td>Aspergillus flavus and Aspergillus parasiticus</td>
<td>Nuts, figs, dates, oranges</td>
<td>tropical, subtropical</td>
<td>broken, damaged peels (nuts), soft mature peels</td>
<td>hepatocarcinogen, retard growth of children</td>
<td>0-50 ppb</td>
</tr>
<tr>
<td>Patulin (PAT),</td>
<td>Penicillium expansum,</td>
<td>apples, pears, apricots, peaches and grapes;</td>
<td>warm weather</td>
<td>broken damaged peel</td>
<td>gastrointestinal lesions</td>
<td>50 μg/litre</td>
</tr>
<tr>
<td>Ochratoxin A (OTA)</td>
<td>Aspergillus Nigri</td>
<td>grapes</td>
<td>worldwide</td>
<td></td>
<td>renal toxicity, nephropathy and immuno-suppression</td>
<td>0.5-50 μg/kg</td>
</tr>
<tr>
<td>Alternaria mycotoxins</td>
<td>Alternaria alternata and others</td>
<td>Most fruits and vegetables</td>
<td>worldwide</td>
<td></td>
<td>Allergies (asthma)</td>
<td>not established</td>
</tr>
</tbody>
</table>

Source: Largely based on Barkai-Golan and Paster (2008)

Mycotoxin accumulation in fruits vegetables can occur in the field/orchard, during harvest, postharvest and during storage. Although consumers will likely reject fresh fruit that is visibly mouldy or rotten, contamination of processed fruit products is hidden and significant amounts of these toxins may occur if decayed or mouldy fruit is not removed before processing. Fruits used for dried fruit production should be dried rapidly and completely, and stored under conditions that prevent rewetting (Jackson, Al-Taher 2008).

Fungal spoilage during postharvest and storage represents serious economic losses to producers. Thus, only sound, intact fruits and vegetables should be stored or used for processed fruit products. Gentle and sanitary handling of the fruit during harvest and in storage and processing facilities is essential for reducing fungal decay and mycotoxin production in fruits. Generally, the refrigerated storage reduces development of fungi and mycotoxin production except for Alternaria. The more targeted protection against fungi and mycotoxins includes: (a) postharvest fungicidal treatment. This treatment is usually effective but less preferable since fruits and vegetables might be contaminated by toxic residuals; (b) modification of atmosphere by reducing oxygen close to zero and increasing significantly CO₂ (up to 40%); (c) ozonification; (d) washing fruits and vegetables in water with hypochlorite or diluted ozone. In contrast to grains, fruits and vegetables are sensitive to low oxygen and high concentrations of carbon-dioxide, thus using these agents in protecting crops against moulds must be done very carefully and only for short time. Alternatively, exposition of fruits and vegetables to ozone (O₃) can significantly stop mould development (Zottia et al. 2008, El-Desouky 2012); however, concentrations must be relatively high (2-3 ppm) and thus the exposition must be only for short time and air circulation must be provided. Moreover, ozone is not effective in reduction of infection of inoculated wounds (Smilanick 2003). Ozone in high concentrations is successfully used to provide sanitation of storage rooms.

More research is needed to identify fruit and vegetable cultivars that are resistant to fungal decay. Fermentation kills mycotoxins, thus these are not present in alcoholic beverages (vine). However, more work is needed to determine the fate of mycotoxins during other processing (Jackson, Al-Taher 2008).
5.2.4. **Benefit of technologies based on cold chain**

The overall benefit of the cold chain technology in terms of reducing postharvest losses of FFV is well illustrated in Table E15. In developed countries where refrigerated storage capacity is high the losses are substantial lower than in developing countries lacking refrigerated storages (capacity per inhabitant is 10 times lower in developing countries than in developed countries). According to the International Institute of Refrigeration (IIR, 2011), more than half of postharvest losses can be attributed to the insufficient refrigerated storage capacity in both regions. The lack of cold chain in developing countries is particularly worrying if we take into account that increasing proportion of their inhabitants live in big urban agglomerations. The world urban population is expected to increase by 72 per cent by 2050, from 3.6 billion in 2011 to 6.3 billion in 2050; most of the expected growth will be concentrated in the urban areas of the less developed regions, whose population is projected to increase from 2.7 billion in 2011 to 5.1 billion in 2050 (UN DESA, 2012). Bringing FFV in these urban areas will be a challenge with which the current system in developing will hardly cope.

Table E15: The effect of cold chain technology on postharvest losses of FFV

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Global</th>
<th>Developed countries</th>
<th>Developing countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population in 2009 (2050 forecast)</td>
<td>billion</td>
<td>6.83 (9.15)</td>
<td>1.23 (1.28)</td>
<td>5.6 (7.87)</td>
</tr>
<tr>
<td>Refrigerated storage capacity</td>
<td>m3 /1000 inhabitants</td>
<td>52</td>
<td>200</td>
<td>19</td>
</tr>
<tr>
<td>Losses of fruit and vegetables (%)</td>
<td></td>
<td>35%</td>
<td>15%</td>
<td>40%</td>
</tr>
<tr>
<td>Losses of perishable foodstuffs through a lack of refrigeration (%)</td>
<td></td>
<td>20%</td>
<td>9%</td>
<td>23%</td>
</tr>
</tbody>
</table>

Source: International Institute of Refrigeration (IIR 2011)

Reefs (2010) describes differences between the traditional FFV marketing systems and the modern one (Table E16). In the developed countries, FFV are produced on large farms, or farms are associated in marketing cooperatives. The FFV supply chain exhibits a significant vertical integration (at least in terms of long term contracts). The consumption is rather continuous (this is also because the international trade allows more or less continuous supply over the year). Under these circumstances, farmers and their cooperatives are ready to invest in postharvest technology. In contrast, traditional systems rely on small farmers and several levels of rather small intermediaries. Often, growth of the production scale is limited by institutions (legally or by informal institutions). Although the system is able to deliver FFV in the urban areas, it provides little incentives and guarantee for investment in postharvest technology. This however is needed in order to reduce losses. The crop is usually insufficiently protected in the production phase (on field, in orchards). Particularly in warm wet weather, mould and bacterially infested crops deteriorate quickly after harvest. Transport is almost entirely in ambient trucks, some perhaps offering protection from the sun. Roads can be very congested and poorly maintained in some
areas. Cold stores (if any) are often multi-user with owners providing a service. Various fruits and vegetables might meet in one storage room with adverse effects each on the other.

Table E16: Characteristics of modern and traditional FFV marketing chains

<table>
<thead>
<tr>
<th></th>
<th>Developed (e.g. EU)</th>
<th>Developing (India) - small farmers</th>
</tr>
</thead>
<tbody>
<tr>
<td>General characteristics</td>
<td>FFV are sourced from large farms or organisations</td>
<td>System is based on small farms (often institutional limits to the farm growth)</td>
</tr>
<tr>
<td></td>
<td>Significantly integrated supply chain, quality control, long shelf life required</td>
<td>Many intermediaries, products flow immediately from hands to hands, lack of quality control</td>
</tr>
<tr>
<td>Preharvest</td>
<td>Extensive chemical and biological protection of the crop</td>
<td>Application of the protection against pests is variable</td>
</tr>
<tr>
<td>Physical protection of the harvested crop</td>
<td>Appropriate, clean containers; Highly perishable, soft FFV packaged immediately after harvest; In other cases after storing</td>
<td>Containers, baskets - rarely disinfected; Packaging at the later stage of the FSC, if any; Protection variable.</td>
</tr>
<tr>
<td>Storage</td>
<td>Refrigerated, CA</td>
<td>Rarely refrigerated</td>
</tr>
<tr>
<td>Transport</td>
<td>Refrigerated</td>
<td>Rarely refrigerated (except for export)</td>
</tr>
</tbody>
</table>

Source: Own structuring largely based on Reefs (2010)

Solutions for the decrease in postharvest losses will require, in many cases, an integrated approach from “seed to supermarket shelf” since many pre-harvest factors do influence postharvest behavior and losses (Hewett 2006). Actually, cold chain can function only as fully implemented, i.e. refrigerated storage – refrigerated transport – refrigerated retail store. In addition, margin throughout the chain might provide funds for technological improvements. Reardon and Minten (2011) argue that recent rapid development of private supermarket chains in India (annual growth by 49%) might represent the necessary power able to transform gradually the whole supply chain in the near future. These retailers concentrate on the needs of the growing middle class whose diet has changed in favour of fruits and vegetables over last 20 years. Thus, we can expect that it will have also its reflection in the development of the FFV cold chain. According to Reardon and Minten (2011) supermarkets, by their push on the supply chain, can stimulate vertical integration which will have capacity to provide a framework for private investment in the FFV cold chain. They call this process top-down revolution in the food supply chain.

Reardon and Minten (2011) also show that the state initiated and cooperative retail sectors not only coexist with the expanding private supermarkets but have kept their power to drive the food sector development in India. Perhaps, we can generalise stressing that all three lines are important for the development of modern supply chain for fruits and vegetables in developing countries.

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13 We are adding
It follows from the description of the FFV postharvest systems that modern technology requires lot of knowledge and skill to manage it properly and thus to reduce the losses effectively.

The knowledge transfer concerns pre- and postharvest crop protection, coatings, fruit treatment systems, new packaging materials and designs and innovative ripening, and cold storage systems as well as understanding the economics of FFV production and distribution. Beside technological and economic knowledge, the modern system requires monitoring and discipline in taking corrective actions in production and postharvest treatment. Targeted (specialized) training and education is needed as well as a support of an operational extension service.

It is more or less clear that not all farmers in developing countries will be able to cope with the knowledge requirements and requirements for standardisation and safety procedures, even if an effective extension service is be established and available. In addition, vertical integration as well as investment costs will require growing in size which under land ownership restrictions in many countries will be achievable only by horizontal cooperation. This will require social capital and taking risk in pooling financial capital and profit. Thus it is very likely that the fruit and vegetable sector modernisation will go hand by hand with structural change which might result in a separation of the progressive urban oriented food chain and marginalised rural semi-subsistence farming.

In developed countries we can expect continuing increasing concentration and vertical integration in the fruits and vegetables sector on one hand, as well as an expansion of short chains delivering local produce to local markets on the other hand. Concerning the former, the strong capital position of the integrated chain will allow investment in progressive technologies, research and education. Although the latter will never dominate the market, these fruit and vegetable producers will be challenged with food safety and reduction of crop losses while sustaining good profit.

5.3. Roots and tubers

Root and tubers (cassava/manioc, yam, sweet potatoes\textsuperscript{14}, potatoes) are rich of starch which makes them staple food in many countries.

Harvest and post-harvest treatment of roots and tubers include four steps

\begin{itemize}
  \item Harvesting roots and tubers from the soil
  \item Sorting and cleaning
  \item Curing (healing of wounds)
  \item Storing
\end{itemize}

Like for cereals and fruits and vegetables, there are traditional and modern technologies of roots and tubers postharvest procedures. Similarly to cereals, roots and tubers are important crop for the subsistence of rural population, but they are also still more demanded by and produced for urban areas and export. It represents an important factor of commercialisation of roots and tubers production. Commercialisation brings with it pressure on productivity and efficiency of crop cultivation as well as postharvest treatment, and thus on modernisation of production and distribution processes.

\textsuperscript{14} Yam (Dioscorea sp.), Sweet potato (Ipomoea batatas) which is sometimes called also yam.
Table E17: Physiological (environmental) factors affecting postharvest of root and tuber crops

<table>
<thead>
<tr>
<th>Factors</th>
<th>Period</th>
<th>Crop</th>
<th>Effect on postharvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy rains - asphyxiation</td>
<td>Pre-harvest, harvest</td>
<td>Sweet potato</td>
<td>Crops decay shortly after harvest</td>
</tr>
<tr>
<td>Drought followed by intensive rains</td>
<td>Pre-harvest, harvest</td>
<td>Yam</td>
<td>Thin skin prone to cracks</td>
</tr>
<tr>
<td>Mechanical damage</td>
<td>Harvest, postharvest</td>
<td>All roots and tubers</td>
<td>Wounds prone to the attack of pathogens</td>
</tr>
<tr>
<td>Exposition to the sun</td>
<td>Harvest</td>
<td>Sweet potato</td>
<td>Scald, it can be site for postharvest decay</td>
</tr>
<tr>
<td></td>
<td>Harvest, postharvest</td>
<td>Potato</td>
<td>Overheating increasing the crop susceptibility to decay</td>
</tr>
<tr>
<td>Chilling injury</td>
<td>Postharvest</td>
<td>Sweet potato, yam</td>
<td>Susceptibility to decay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potato</td>
<td>Starch is converted in sugar</td>
</tr>
</tbody>
</table>

Source: Various sources referred in this chapter

Harvest and postharvest losses of roots and tubers can be classified as physiological (caused by the effect of environmental conditions), pathological (caused by the attack of pathogens, e.g. fungi, bacteria, insects etc.) and endogenous (caused by endogenous processes like respiration, transpiration and sprouting). Of the four mentioned crops, cassava is very difficult to store and therefore is processed quickly after harvest.

Reducing harvest and postharvest losses is essential for improving food security of small (semi)subsistence farmers and poor rural households for which potatoes, sweet potatoes, yams and cassavas are principal food as well as for improving efficiency of the distribution system delivering food to urban population.
Table E18: Pest affecting postharvest of root and tuber crops

<table>
<thead>
<tr>
<th>Pests</th>
<th>Period (of infestation)</th>
<th>Crop</th>
<th>Effect on postharvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacterial rot (e.g. Erwinia sp., Corynebacterium manihot)</td>
<td>Pre- and post-harvest</td>
<td>All</td>
<td>Decay of the crop</td>
</tr>
<tr>
<td>Fungal rot (Fusarium sp., Aspergillus sp., Rhizopus sp., etc.)</td>
<td>Pre-harvest and harvest (in soil), postharvest</td>
<td>All</td>
<td>Decay of the crop &amp; mycotoxin</td>
</tr>
<tr>
<td>Insect pest</td>
<td>Pre- and post-harvest</td>
<td>All</td>
<td>Wounds prone to the attack of bacterial and fungal pathogens</td>
</tr>
<tr>
<td>Nematodes pest</td>
<td>Pre-harvest</td>
<td>Yam</td>
<td>Wounds prone to the attack of bacterial and fungal pathogens</td>
</tr>
</tbody>
</table>

Source: Various sources referred in this chapter

Weather extremes, exposition to extreme temperatures (high, low) during pre- and postharvest and rough handling are main factors of physiological losses. They not only reduce the value of the crop due to damaged appearance, but temperature or mechanical injuries can be followed by invasions of pathogens leading in the decay of the attacked crop in the storage. Some weather effects can be hidden having tremendous impact on crop storage: for example heavy rains close to harvest that saturate soil for more than a few hours can cause sweet potato asphyxiation. Water-saturated soil allows carbon dioxide to accumulate\(^{15}\) in the roots/tubers. Asphyxiation can happen at any time, but it is more likely to occur during warm periods, especially if the foliage has been removed before harvest. Sweet potatoes that have been asphyxiated may appear healthy for several days or weeks, but if injury was severe, the roots will die and begin decomposing in storage (Edmunds et al. 2007).

The wound type and the level of damage have a big influence on the development of postharvest rots. Scuffs, where the skin is broken and some bruising occurs, splits and skin grazes, etc. are entry points for rots (Edmunds et al. 2007; Opara 2003; Meyhuya 2001). Uninjured and cured tubers do not develop postharvest rots (Jobling 2000). The damages are caused by harvesting instruments and handling as well as by insects, nematodes (yam) and rodents (see Table E18). Often, the effect of damages does not become evident until several weeks after harvest.

While bacterial rots lead to a rapid decay of tubers and roots, most moulds are also toxical; mycotoxins spread through the root/tuber and even if the infected part is removed, the rest of the root/tuber is poisonous. Fusarium and Rhizopus fungi usually come from the soil while Aspergillus is a typical post-harvest mould. Number of authors (e.g. Gnonlonfin et al. 2008) state that, particularly in tropical Africa, the presence of mycotoxins is high in yam and cassava roots as well as in dried chips.

Earlier publications on the deterioration of cassava simply stated that cassava roots were highly perishable and would not store well, definitely not for more than a few days. The current research shows

\(^{15}\) It may also be accompanied by a depletion of oxygen.
that the subject is more complex and that the crop decay is always caused by more than one factor and one microorganism (Wenham 1995). Further research in this area is desirable in order to suggest effective postharvest and storage methods.

With high temperature and after the natural dormancy period, tubers tend to sprout. With sprouting, both respiration and moisture loss will increase rapidly, lowering the value of the crop.

5.3.1. **Pre-harvest and harvest**

Successful storage starts with high-quality roots/tubers. Events occurring during the growing season may later negatively affect postharvest quality. Some factors such as weather are impossible to control, whereas others (such as fertilization) can be managed by a grower to ensure that a quality product goes into storage.

Traditional harvesting of roots and tubers is done by hand using sticks, spades or diggers; simple mechanisation is used for potatoes, sweet potatoes, cassava and some smaller varieties of yam. Advanced mechanisation is used only for potatoes and sweet potatoes, usually, in order to reduce labour intensity in commercial farming systems. In contrast, yam and cassava harvests remain heavily labour intensive also in countries producing these crops for export (Bokanga 1999; Opara 2003). The success in mechanical yam harvesting has been limited to the use of a potato spinner for harvesting species which produce a number of small tubers. The technical constraint to the mechanical harvest of yam and cassava rests in size and distribution of tubers and roots in the soil. The dominance of small-scale farms represents an institutional constraint to the spread of mechanisation in root and tuber production. Extensive changes in current traditional cultivation practices and perhaps some physical properties of crops, farm size and changes in social context (outflow of labour) will be needed to stimulate demand for mechanisation (Opara 2003).

5.3.2. **Sorting and cleaning**

During sorting, ground, stones, vegetal wastes, cut or rotten tubers/roots are separated. Sorting is achieved manually or with sorting machines. The second case offers advantages such as efficiency. Whichever method is chosen, potato contusions or bruising should be avoided. The quality of harvested tubers is the most important factor that affects the outcome of any (short/long term) storage system.

Generally, use of water should be avoided before long term storage of tubers/roots, since it increases susceptibility to microbial infection and growth (Opara 2003; Edmunds et al. 2007). Potatoes can be washed before storage, provided that they are fairly dried afterwards (Jobling 2000).

Relatively clean tubers sold in the local market may not require any further cleaning. However, many urban and export markets require yams, sweet potatoes and potatoes to be washed. Yam should be washed by hand in clean water with hypochlorous acid to remove any remaining dirt and to sanitize the tuber surface (NGMC 2013). Mechanical washing can be used for potatoes and sweet potatoes if the produce quantity is large (Meyhuay 2001; Edmunds et al. 2007). Washed tubers/roots must be dried before packaging.

5.3.3. **Curing**

Because of tiny skin and fragility of the root or tuber crops, harvest damages are not fully avoidable, even if the harvest is done by hand. Cuts and bruises are strongly susceptible to attacks of pathogens. On the other hand, roots and tubers exhibit self-ability of healing. Curing should be carried out as soon as possible after harvest.

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16 e.g. cassava in Thailand
17 Clean water is a necessary precondition, some disinfection can be added.
Regardless of which crop is to be cured, the roots and tubers must be kept at the right (normally above ambient temperature) temperature to stimulate skin healing. Traditionally, yams are cured by drying the tubers in the sun for a few days. The optimum conditions for yam curing are 29°-32°C at 90-96% relative humidity for 4-8 days. It can be combined with gamma radiation (Opara 2003). The most simple curing practice for sweet potato in the Eastern Caribbean involves simple stacking of the produce in in small heaps, off the ground in a shaded, sheltered and well ventilated spot under ambient conditions. The curing process should be completed in 3 to 5 days (Edmunds et al. 2007). Curing of potatoes is carried out by maintaining tubers at temperatures from 16°C to 21°C with 90% relative humidity during approximately 10 to 15 days (Meyhuay 2001).

In general, good ventilation should be provided so that oxygen is supplied, and the air around the roots or tubers must be kept moist but without free moisture on the surface; dry air will cause injured surfaces to dry out quickly while free moisture will allow spoilage organisms entry into the tuber before the protective layer forms. To control humidity, humidification equipment (humidifiers) and measurement devices (psychrometer or electronic sensors) should be used. Modern facilities are also equipped with a powerful fan which is able to provide uniform conditions of temperature and humidity throughout the mass of roots/tubers.

Unfortunately, roots and tubers are stored and traded without a proper curing treatment in many developing countries. Often the uncured tubers are bundled straight into poorly ventilated bags with damp soil still attached to the surface, roughly handled and loaded into trucks. Then crop is prone to decay and postharvest losses are very high.

5.3.4. Storage

Only sufficiently dried and clean crop should be put in the storage. Temperature and humidity must be controlled during storage: The optimum storage temperature for potatoes depends on their final use. It is recommended that fresh market potatoes are stored between 5 to 6°C. Potatoes that are used for making chips are stored between 7 and 10°C. The difference in temperature is due to the fact that potatoes for chips need to have low levels of sugars. High sugar levels (created when temperature is low) result in chips with a dark brown colour rather than the golden colour consumers prefer (Jobling 2000).

Sweet potatoes and yam tubers are chilling sensitive. Sweet potatoes and yam should be stored at 13°C and between 12.5°C and 15°C respectively, with high relative humidity over 90%. A storage life of 13 and 6-10 months (respectively) can be expected under these conditions (Opara 2003; Edmunds et al. 2007).

Respiration of tubers produces heat which is to be conveyed away by ventilation. The forced ventilation (by a fan of sufficient capacity) is often needed to provide more effective heat transfer than can be achieved by natural ventilation. To safeguard the effective heat transfer, the crop should be stored in the way that forced air can reach each tuber. Thus, the type of ventilation and the form and organisation storage (sacks, containers, or bulk storage) must be harmonised.

Higher temperature and long storage will lead to sprouting. Sprouting contributes to weight and quality losses as it was pointed out earlier. The use of sprouting inhibitors is recommended for long term storage.

The skin and pulp of the potato tubers form a green coloration if exposed to the light (the sun); these produce chlorophyll and solanin. The green spots are of bitter flavour and solanin can end up being toxic. The avoidance of greening is achieved with dark storage (diffuse light).

Storage facilities should not only assure proper temperature and humidity, but also protection against rodents and insects. In spite of following the basic principles of the proper storage, traditional facilities

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18 Osunde (2008) cites research on the benefits of gamma irradiation of yam for delaying sprouting and reducing crop decay.
for potatoes, sweet potatoes and yam (field piles, warehouses, yam barns or underground structures) often give little possibility for controlling temperature and humidity and usually provide poor protection against rodents and pests.

In contrast, the modern warehouses are usually air conditioned, refrigerated and well protected against insects and rodents. However, these are not affordable for small semi-subsistence farmers. Thus the surplus crop tends to be sold immediately after harvest. Nevertheless, there is still space for the improvement of the traditional technologies and the enhancement of knowledge and skill of small semi-subsistence farmers in order to save most of the harvest, thus reducing losses. It involves improvements of pre-harvest and harvest techniques, curing and rodents and insect protection of storage facilities with materials largely available to small farmers (Meyhuay 2001; Opara 2003). The Central Potato Research Institute (India) and the International Potato Center investigated the use of evaporatively cooled structures (ECS)\(^\text{19}\) to lower temperatures inside a store. According to Fuglie (1999), average losses after three months of storage were reduced from around 24 percent of initial weight in farmers’ clamps to only 10 percent in ECS. However, ECS involves higher construction and maintenance costs compared with traditional methods. Acceptance of the technology by farmers depends on whether the benefits from lower losses and higher prices are sufficient to offset the additional storage construction costs.

Investments in the modern storage facilities (and generally in the postharvest technology) become realistic with commercialisation of the root and tuber production, and consequently with development toward bigger entrepreneurial structures (either enlarged farms or farmers’ cooperatives) and integration of the marketing chain. Similarly to grains, and fruits and vegetables, such a transformation will require institutional preconditions in terms of commercial legislation and its enforcement, and enhanced social capital (for both the collective action of farmers as well as for fair commercial relationships).

There are reports that indigenous growers of cassava (American Indians) stored roots for months. These reports have been followed by several attempts to construct current cassava storages, however, so far, they all have failed due to inability to control effectively temperature, humidity and the development of moulds (Bokanga 1999).

5.3.5. Drying

Because of the perishability of cassava (and also their size), roots are chipped, dried and then stored. The first step in processing cassava roots in chips is to remove the peel\(^\text{20}\). Peeling is usually done by hand using a knife. The peeling process by hand is slow and labour-intensive, with about 25 kg per man-hour. Mechanical peelers are generally wasteful and with low efficiency. All solutions, including chemical ones that have been developed so far, have proved rather impractical (Bokanga 1999).

Traditionally and at the home level, manual chipping of cassava roots is slow and produces large and irregular chips that take 3 to 7 days to dry. Mechanical chippers have the advantage of producing smaller and uniform chips that dry rapidly. The drying rate depends on the geometry of the chips and the amount of chips per unit of drying surface. Finger chips of about 5mm thickness and a length depending on the size of the cassava roots can dry after 6 to 8 hours of exposure to the sun. When manually operated, the chippers have a capacity of about 60-70 kg/hr; but an electric, gasoline or diesel engine can power them with a capacity of 1000kg/hr (Bokanga 1999).

\(^\text{19}\) In evaporative cool storage (ECS) a pan of water is maintained beneath the store and potato tubers are cooled as evaporating water is drawn into the storage structure; suitable only if air is sufficiently dry - in the damp weather evaporation is substantially reduced.

\(^\text{20}\) This result in a great reduction the cyanogenic potential of the raw material, because the peel represents about 15 percent of the weight of the root, and its cyanogen content is usually 5 to 10 times greater than that of the root parenchyma (Bokanga 1999).
5.3.6. Options for reducing losses of roots and tubers

At many points, we stressed that production, harvest and postharvest technologies must be harmonised if losses are to be reduced. For potatoes and sweet potatoes such harmonised modern technologies exist and not only at large scale. There are many small growers\(^{21}\) in developed countries who produce, store and sell quality crop. Potato and sweet potato harvest and postharvest can be largely mechanised, labour requirements have declined significantly over last decades. The postharvest treatment of roots and tubers tends to be organised on farms. Nevertheless, cooperative postharvest facilities are common too. There are also commercial storages, usually owned and organised by merchants and processors\(^{22}\). There are some benefits of scale, therefore, modern technologies tend to be adopted by large businesses. Modern technologies require a certain degree of integration within the food chain because postharvest operations depend also on the final use of the crop. In addition, investment costs are rather high and assets specific, thus good links to market are necessary (preferably long term contracts). Storing crop enables producers to market their production when prices are good. In contrast, small farmers must often sell their surplus production immediately after harvest.

Modern potato and sweet potato technologies exist in parallel with the “traditional”\(^{23}\) ones, located in poor small farms in transitional (e.g. India, China) and developing countries. Limited capacity of small farmers to adopt new technologies (particularly when farm growth is institutionally limited) is recognised in India. Small farmers can deliver their potato crop to “scientific” storages and they can receive easy marketing credit against the stored produce (AGMARKETNET). The system is similar to the system for cereals, however, relying more on private storages. Because storage rents are administratively fixed on one side and potato prices highly volatile, the system performance is rather variable. Concerning the fixed storage rents, if the resulting storage margin is low, private investors are discouraged (Dahiya et al. 1996); concerning the volatile prices, if the market rent due to later sales is risky, farmers do not want to bear the costs of storage (Fuglie 1999). In addition, local markets might dislike potatoes from cold storage (Dahiya et al. 1996). Consequently, if the current facilities are not sufficiently used for storing potatoes, private owners will tend to rent them also for other crops which will likely result in high losses and declining quality of all stored products.

Except some small tuber varieties of yam, yam and cassava harvests will likely remain highly labour intensive. Introducing mechanisation in the postharvest process has appeared rather problematic. On the one hand, producing yam and cassava provides employment and income for rural dwellers, particularly if yam and cassava-based agro-industries develop around farms. On the other hand, high labour intensity might go against the production of these crops with economic development (particularly, if the opportunity cost of labour increases).

5.4. General conclusions on technological options for reducing crop losses

Based on the analysis of the three categories of crops (grains, fresh fruits and vegetables, roots and tubers), the following general conclusions can be drawn:

> Postharvest losses are closely linked to pre-harvest and harvest technologies. Biological spoilage has its roots in poor protection against pests during the growing period, inadequate timing of harvest and rough handling during harvest and during the transport from the field to the postharvest facilities.

\(^{21}\) Often part-time farmers or hobby farmers, supplying local markets.

\(^{22}\) In India also by the government.

\(^{23}\) One has to be careful with this word – these are rather mixed technology systems with rather poor control of pests.
> Damaged and infected crops should not be put in the storage (neither short term nor long term). Damaged kernels, fruits, leaves, roots, tubers, etc. must be sorted out in the post-harvest process.
> Modern harvest and post-harvest mechanisation is usually gentle, and the research and development of these technologies goes in the direction of providing effective, gentle and economically efficient treatment of crops.
> Whenever it is useful to wash the crop (before or after storage), it is necessary to use clean water, possibly with some disinfection. After washing, the crop should be dried before storing or packaging in most cases.
> The surface of stored crops should always be dry.
> Storage of either crop requires controlling temperature and humidity, and often also the content of oxygen and carbon dioxide (grains and FFV).
> If a crop is not CO2 sensitive, high concentrations of it (and low concentrations of O2) will treat against biological pathogens and insect pests.
> Controlling temperature and atmosphere requires not only facilities but also monitoring and control systems, which might be fully automatic, but if they require human input, the knowledge, skill and discipline of the staff is critical.
> Because biological processes of stored crops are never stopped, appropriate ventilation is needed to provide transfer of heat and to avoid condensation of water in wet spots.
> Except for some roots and tubers, effective (in terms of low losses) pre-harvest, harvest and postharvest technologies exist and are basically available anywhere in the world (so called modern technologies).
> Usually, there are high investment costs associated with modern technologies, while running costs are low or moderate. There are economies of scale, thus they are suitable for large farmers, group of farmers (cooperatives) or large merchants and processors. A certain level of technical infrastructure is necessary.
> Because of high investment costs and large quantities stored, integration with the rest of the food chain is necessary.
> In most cases however, modern technologies are not affordable for small-scale farmers, particularly semi-subsistence farmers. Sometimes they are not suitable in scale too; even small mechanization is able to process harvested crop in a couple of hours.
> There are attempts to solve the postharvest problems of small-scale farms by encouraging them to deliver their surplus crop (e.g. cereals, potatoes) as soon as possible into large scale “scientific” i.e. proper postharvest-storage facilities, usually under conditions regulated by the government. This is generally beneficial (at least in short run), however, it has also adverse effects – either too much outflow of crops from rural areas (cereals in India) or insufficient use of these large scale facilities. There are many reports of high losses in these facilities due to improper management (likely resulting from rather unprofitable business).
> Commercialisation of farming can contribute to the reduction of postharvest losses, particularly if it goes hand by hand with farm structure development toward larger scales, either by increasing farm size or by creating producers’ cooperatives. The effects are amplified by stable trading condition, safeguarded contracts and more integrated vertical relationships (particularly in the case of FFV). These institutional changes should be facilitated by the governments.
> For poor small-scale farmers / semi subsistence farmers, the way how to reduce postharvest losses remains in improving the traditional technology and enabling their participation in the modern food supply chain. The technological improvements must be of low cost using locally available materials and tailored to the local climatic, natural and socio-economic environment.
Modern and improved technologies require knowledge, skill and in many cases effective extension services. Many governments, international governmental and non-governmental organisations invest in knowledge transfer, education of farmers, as well as in research to address locally eminent technological issues. It seems however, that bringing knowledge to farmers is not a straightforward process.

Past experience shows that the support system cannot be exclusively technically focused (Parfitt 2010; Kitinoja et al. 2011); in contrary, more types of intervention are needed: “institutional” providing effective rules, knowledge transfer support, improved access to credits and often direct market intervention providing stabilisation through temporary storage of surpluses. In addition, producers must be guided to see a clear direct or indirect advantage, particularly financial benefit.

In summary, building on this and the Phase 1 reports we argue that the issue of reduction of postharvest losses should be understand in the broader technological and institutional context: First, crop losses depend on a number of factors including those which are beyond the control of farmers; to address them simultaneously requires knowledge, professional training and extension support. Second, modernization of harvest and post-harvest technologies usually needs investment for which many farmers in developing countries have no resources. Causes can be that farms are too small and primarily produce for their own consumption (e.g. subsistence farms in Sub-Saharan Africa), or that the financial flow in the marketing system is inefficient (e.g. Kazakhstan). Third, often farmers are not integrated in markets; there are many intermediaries and the system is largely inefficient. Fourth, infrastructure is poor and the government has no means or interest to invest in it. Fifth, as it has already been pointed out, often improving one operation in the FSC (e.g. introducing high yield varieties) requires adjustment/improvement of the follow up activities of which farmers are neither aware nor have skill nor financial means to address them. Both the technological and organisational/institutional solutions should go hand by hand.

Hodges et al. (2010) following World Bank (2010) argues that some of the improvements for reducing post-harvest losses in least developed countries will need to take the form of public ‘goods’ including market organisation and infrastructure such as the development of networks of all-weather feeder roads so that crops can get to market, a problem especially acute in Africa.

Good examples can be find in India, Brazil, Argentina, among international research institutes of CGIAR: the International Rice Research Institute (IRRI), The International Maize and Wheat Improvement Center (CIMMYT), The International Potato Center (CIP) etc.
REFERENCES


Agriculture Solar (2013): http://www.agriculturesolar.com/3b_drying_process_of_solar_grain_dryer.html#Ua8RfkBM_Ns; accessed on 05.06.2013


Breth, S (1976). Asian farmers can adopt Guatemala’s low cost metal silos. Mod. Agric. Ind.Asia (Philippines), April 1976


Hodges, R.J., Buzby, J.C., Bennett, B. (2010): Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. The Journal of Agricultural Science 149 (S1), 37-45.


http://www.indiaagronet.com/indiaagronet/Agri_marketing/contents/Storage%20and%20Warehousing.htm

http://www.extension.iastate.edu/agdm/crops/html/a2-33.html; accessed on 07.06.2013


http://www.crosstree.info/Documents/Care%20of%20F%20n%20V.pdf


Maloney, B. (2010): Post-harvest handling guide for Moldovan peaches and nectarines. USAID.


SeedBuro (2013):  
http://www.seedburo.com/productDetail.asp_Q_catID_E_517_A_subCatID_E_2583_A_productID_E_3177; accessed on 07.06.2013.


http://postharvest.tfrec.wsu.edu/PC2003H.pdf


http://blog.chamber.ua/2011/04/expert-view-agricultural-sector-ludwig-striewe

http://www.unu.edu/Unupress/food/8F042e/8F042E05.htm

http://vric.ucdavis.edu/postharvest/undergnd.htm


This document is the annexes to the final report of the STOA study ‘Technology options for feeding 10 billion people - Plant breeding and innovative agriculture’.

A summary and an ‘Options brief’ related to this study are also available.

The STOA studies can be found at:
http://www.europarl.europa.eu/stoa/cms/studies
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