Conservation agriculture: synergies of resource-conserving technologies in rice-based systems[1]

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BACKGROUND

In 2000, about 850 million people were suffering from hunger, 815 million of which in developing countries. From a global perspective, hunger is a problem not of food production but of accessibility, since to date world food production has kept pace with demand (FAO, 2006). Although recent predictions point to reduced population growth, a considerable increase in overall production is still required – a major challenge, given the already stretched land and water resources. Future yield increases may be limited compared to past trends (FAO, 2006), but by 2030, food production must double to keep pace with demand.

The production of renewable resources is increasingly important, due both to the growing awareness of sustainability and to rising oil prices. Countries producing a food surplus could in future focus more and more on the production of profitable renewable raw material for industrial products and energy rather than simply on the production of food (FAO, 2002).

There are also regional differences to be taken into account. Sub-Saharan Africa remains a hunger hot spot with a stagnating trend in per capita food production, while other regions are seeing a steady increase (FAO, 2005). Countries with a large population like China and India, and which in the past achieved food self-sufficiency, now face the challenge of maintaining and increasing high yield levels in a scenario of increasing climatic variability.

Over the last few decades the growth in agricultural production has come mainly from yield increase and to a lesser extent from area expansion. Now the agricultural land available per capita is expected to decline (FAO, 2002) while revolutionary technologies for significantly higher production potential do not seem to be in sight. Furthermore, in high intensity agricultural production areas, yield increase seems to have reached a ceiling despite higher input use; in some cases, yields even decline, for example in the grain-producing areas of Punjab in India (Aulakh, 2005).

Water is one of the most precious natural resources for agricultural production and agriculture accounts for 70 percent of water use (FAO, 2002). It is predicted that by 2025 water consumption will exceed "blue water" availability if current trends continue (Ragab and Prudhomme, 2002). In the Indian state of Punjab, characterized by intensive irrigated agriculture, the groundwater table is falling at a rate of 0.7 m per year (Aulakh, 2005). However, the decline of freshwater resources is due not only to increased consumption, but to careless management. Agriculture contributes to the problem by wasting water and by sealing and compacting the soils so that excess water cannot infiltrate and recharge the aquifer – one of the causes of the growing number of flood catastrophes (DBU, 2002). In regions where water is already the limiting factor for agricultural production, this wasteful practice threatens the sustainability of agriculture. Rising temperatures and evapotranspiration rates combined with more erratic rainfall further aggravate the water problems in rainfed agriculture (Met Office, 2005).

Soil affects not only production, but also the management of other natural resources, such as water. Soil structure is strongly correlated with the organic matter content and the soil life. Organic matter stabilizes soil

[1] The views expressed in this paper are the personal opinion of the authors and do not necessarily quote the official policy of FAO.

aggregates, provides feed to soil life and acts as a sponge for soil water. With intensive tillage-based agriculture, the organic matter of soil is steadily decreasing, leading first to a decline in productivity, followed by the visible signs of degradation and finally desertification (Shaxon and Barber, 2003). The lack of yield response to high doses of fertilizer in the Indo-Gangetic Plains can be attributed to poor soil health resulting from over-exploitation (Aulakh, 2005). In the Indian states of Uttaranchal and Haryana, the organic carbon content in soils reaches minimum values of less than 0.1 percent (PDCSR, 2005). While soil degradation is more pronounced in tropical regions, it is also a phenomenon in moderate climatic zones; indeed, the world map of degraded soils indicates that nearly all agricultural lands show some level of soil degradation (FAO, 2000).

RESOURCE-CONSERVING TECHNOLOGIES

Resource-conserving technologies (RCT) have been developed in order to:

- reduce the use of and damage to natural resources through agricultural production; and
- increase the efficiency of resource utilization.

Most of these technologies target the two most crucial natural resources: water and soil, but some also affect the efficiency of other production resources and inputs (e.g. labour, farm power and fertilizer). Some of the more popular RCTs, particularly in irrigated or rice-based cropping systems, are described below.

Laser levelling

For surface irrigated areas it is essential to have a properly levelled surface with the appropriate inclination for the irrigation method adopted. Traditional farmers' methods for levelling by eyesight are not sufficiently accurate (particularly on larger plots), resulting in extended irrigation times, unnecessary water consumption and inefficient water use. The use of laser-guided equipment for the levelling of surface-irrigated fields has become economically feasible and accessible – through hiring services – even to lower-income farmers. Laser levelling reduces the unevenness of the field to about ±2 cm, resulting in better water application and distribution efficiency, improved water productivity, increased fertilizer efficiency and reduced weed pressure. Savings of up to 50 percent in wheat and 68 percent in rice have been reported (Jat *et al*., 2006).

Bed planting

Bed planting refers to a cropping system where the crop is grown on beds and the irrigation water is applied in furrows between the beds. This is common practice for row crops, but not for small grain crops such as wheat and rice. The technique offers a number of advantages, such as improved fertilizer efficiency, better weed control and reduced seed rate. It also saves irrigation water compared to a flat inundated field: the evaporation surface is reduced and water application and distribution efficiency are increased. In addition, the rooting environment is changed and the aeration of the bed zone is better than in flat planting. Reported water savings (compared to flat surfaces) reach 26 percent for wheat and 42 percent for transplanted rice, and yield increases 6.4 percent for wheat and 6.2 percent for rice (RWC-CIMMYT, 2003).

Direct seeding

Direct seeding of rice – compared with transplanting – may be considered an RCT:

- It saves labour and fuel.
- Seeding into dry soil saves water as there is no puddling.
- The total growing period from seed to seed is reduced by about 10 days.
- Yields and water efficiency of the subsequent rotation crops are increased (PDCSR, 2005).

On the other hand, weed management is more difficult in dry direct-seeded rice than in puddled and transplanted rice (RWC-CIMMYT, 2003).

Reduced tillage, zero tillage

Intensive soil tillage is the main cause of reduced soil organic matter and hence of soil degradation. Tillage accelerates the mineralization of organic matter and destroys the habitat of the soil life. On the contrary, when soil tillage is reduced or eliminated, soil life returns and the mineralization of soil organic matter slows down, resulting in better soil structure. Under zero tillage the mineralization of soil organic matter can be reduced to levels inferior to the input, converting the soil into a carbon sink (Reicosky, 2001). Zero tillage also results in water saving and improved water-use efficiency: since the soil is not exposed through tillage, the unproductive evaporation of water is reduced while water infiltration is facilitated (DBU, 2002). The potential water saving through zero tillage varies according to the cropping system and the climatic conditions. On average, water savings of 15 to 20 percent can be expected (PDCSR, 2005). Used in isolation, however, zero tillage can lead to problems with weed control, compaction or surface crusting, depending on the soil type.

Mulching and green manure

The supply of organic matter to the soil through mulching and green manure is important for maintaining and enhancing soil fertility. Mulching material can come from crop residues or green manure crops; it provides feed for the soil life and mineral nutrients for the plants. If legume crops are used as green manure they can supply up to 200 kg/ha of nitrogen to the soil; in the case of rice, this can result in mineral fertilizer savings of 50 to 75 percent (RWC-CIMMYT, 2003). The spreading of mulch on the soil surface reduces evaporation, saves water, protects from wind and water erosion, and suppresses weed growth.

Controlled traffic farming

Controlled traffic farming restricts any traffic in the field to the same tracks. While these tracks become heavily compacted, the rooting zone does not at all, resulting in better soil structure and higher yields. The area lost in the traffic zones is easily compensated for by better growth of plants adjacent to the tracks so that overall yields are usually higher than in conventional systems with random traffic (Kerr, 2001). Controlled traffic farming is the ideal complement to zero tillage or to bed planting systems, but it also provides advantages in conventional agriculture through time and fuel savings, since resistance to soil tillage in the compaction-free rooting zones is significantly lower and traction is more efficient when tyres work on compacted tracks (RWC-CIMMYT, 2003). In the latter case, either GPS (global positioning system) guidance or visible bed and furrow systems must be used to limit the tillage operation to the rooting zones and to not disturb the tracks.

SYNERGIES BETWEEN RESOURCE-CONSERVING TECHNOLOGIES

Resource-conserving technologies provide scope for synergy, for example, between bed planting and controlled traffic or mulching and zero tillage. Used in isolation, any of these technologies may face specific problems (e.g. surface crusting or weeds in direct seeding rice) or have limitations (e.g. zero tillage under irrigated conditions). The combination of resource-conserving technologies working in synergy is commonly referred to as "conservation agriculture" (CA).

Conservation agriculture

Conservation agriculture (CA) is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits with high and sustained production levels while conserving the environment. CA is based on enhancing natural biological processes above and below the ground. Interventions such as mechanical soil tillage are reduced to an absolute minimum, and external inputs – e.g. agrochemicals and nutrients of mineral or organic origin – are applied at an optimum level taking care to not interfere with or disrupt the biological processes. CA is characterized by three interlinked principles:

- minimum mechanical soil disturbance throughout the entire crop rotation;
- permanent organic soil cover; and
- diversified crop rotations in the case of annual crops or plant associations in the case of perennial crops.

During the last decade, CA has been gaining in popularity throughout the world and is now applied on about 95 million ha (Derpsch, 2005). Together with other organizations and stakeholders, FAO has been promoting and introducing CA in several countries in Latin America, Africa and Asia. CA adapts to different climatic conditions from the equatorial tropics to the vicinity of the polar circle and to different crops and cropping systems, including vegetables, root crops and paddy rice.

Zero tillage

When the soil is not tilled, the soil structure changes. A system of continuous macropores is established, facilitating water infiltration and soil aeration as well as root penetration into deeper zones. Soil organic matter content increases, with higher values near the surface, gradually decreasing with depth. Soil macro- and microfauna and flora is re-established resulting in better soil fertility.

Soil cover

The permanent soil cover through crops, mulch or green manure cover crops complements the effects of zero tillage by supplying substrate for soil organic matter build-up and for the soil life which is facilitated by not disturbing the soil. By protecting the soil surface, the mulch reduces evaporation, avoids crusting and suppresses weed growth. Problems experienced in direct seeding or zero tillage (applied in isolation) are thus reduced. It should also be noted that the application of zero tillage and direct seeding facilitates the management of residues which in conventional systems are often considered a problem.

Crop rotation

In addition to the phytosanitary and weed management benefits, crop rotation serves to open different soil horizons with different rooting types. While conventional agriculture "cultivates the land", using science and technology to dominate nature, conservation agriculture tries to "least interfere" with natural processes. Similar thoughts have been developed over the past 50 years in the Far East by Masanobu Fukuoka (1975) and applied in rice-based farming.

Permanent beds

In systems where surface irrigation is applied, bed planting results in water saving. Under CA, the beds are converted into permanent beds and soil tillage is limited to a periodic cleaning and reshaping of the furrows. The same permanent bed system is applicable under conservation agriculture also for crop rotations, which include crops grown on beds (e.g. for drainage purposes). The furrow distances and bed width must be harmonized for all crops in the rotation and for all mechanized traffic operations. In this way a permanent bed system leads also to controlled traffic, another RCT.

Direct seeding

Direct seeding is another complement to CA. Although transplanting of crops, including paddy rice, is possible under zero tillage, direct seeding is preferable for the reasons mentioned above. Direct seeding results in less soil movement than transplanting, which often involves some sort of strip tillage. CA facilitates direct seeding by reducing a number of problems encountered when direct seeding is applied in isolation (e.g. surface crusting or weed control).

Laser levelling

The benefits of laser levelling in conservation agriculture are as for conventional agriculture under surface irrigation conditions. To begin with, significant soil movement is required, and so laser levelling is considered an initial investment before converting to a permanent zero tillage cropping system (i.e. conservation agriculture). The investment in laser levelling lasts much longer than in conventional systems, since under CA no further soil tillage (which could upset the levelling of the field) is applied.

Effects of CA

Under CA the levels of soil erosion are inferior to the build-up of new soil. The soil under CA "grows" at an average rate of 1 mm per year due to the accumulation of soil organic matter. This growth continues until a new point of saturation is reached in the soil which takes 30 to 50 years (Crovetto, 1999). The organic matter levels rise by 0.1–0.2 percent per year due to the residues left on the soil surface, the remaining root biomass and the reduced mineralization. Within a crop rotation, different root systems structure different soil horizons and improve the efficiency of the soil nutrient use. In general the soil structure becomes more stable (Bot and Benites, 2005).

Soils under conservation agriculture also improve water efficiency. The increased amount of continuous vertical macropores facilitate the infiltration of rainwater into the ground and help recharge the aquifer. The increased soil organic matter levels improve the level of water accessibility to plants: 1 percent of organic matter in the soil profile can store water at a rate of 150 m^3/ha. The permanent soil cover and the avoidance of mechanical soil tillage reduce the unproductive evaporation of water, water-use efficiency is increased and a crop's water requirements can be reduced by about 30 percent under both irrigation and rainfed conditions (Bot and Benites, 2005). In addition to the quantitative benefits, reduced leaching of soil nutrients and farm chemicals together with reduced soil erosion lead to a significant improvement in the water quality in watersheds where CA is applied (Bassi, 2000; Saturnino and Landers, 2002).

CA can reduce the overall requirement for farm power and energy for field production by up to 60 percent compared to conventional farming (Doets, Best and Friedrich, 2000). This is due to the fact that the most power-intensive operations, such as tillage, are eliminated and equipment investment, particularly the number and size of tractors, is significantly reduced (Bistayev, 2002). CA produces a decline in the use of agrochemicals due to enhanced natural control processes: natural control of pests and diseases improves over time and experience in weed management through crop rotations also facilitates this long-term decline in agrochemical use (Saturnino and Landers, 2002). The same is true for mineral fertilizer: less fertilizer is lost through leaching and erosion and the different rooting systems recycle more soil nutrients from a larger soil volume, resulting in improved overall efficiency of fertilizer use in the long term with a significant reduction in the fertilizer requirements to maintain the production and soil nutrient levels over the crop rotation (Saturnino and Landers, 2002).

Climate and climate change

Recent decades have seen an increase in the frequency and strength of harsh climatic events, including very high precipitations as well as extended drought periods and extreme temperatures (Met Office, 2005). Agricultural production systems are highly vulnerable to these changes.

Conservation agriculture can assist in the adaptation to climate change, by improving the resilience of agricultural cropping systems and making them less vulnerable to abnormal climatic situations. Better soil structure and higher water infiltration rates reduce the danger of flooding and erosion following high intensity rainstorms (Saturnino and Landers, 2002). Increased soil organic matter levels improve the water-holding capacity and hence the ability to cope with extended drought periods. Yield variations under CA in extreme years (dry or wet) are less pronounced than under conventional agriculture (Shaxon and Barber, 2003; Bot and Benites, 2005).

But CA also helps mitigate the effects of climate change, at least with regard to the emission of greenhouse gases. With the increasing soil organic matter, soils under CA can retain carbon from carbon dioxide and store it safely for long periods of time. This carbon sequestration continues for 25 to 50 years before reaching a new plateau of saturation (Reicosky, 2001). The consumption of fossil fuel for agricultural production is significantly reduced under CA and burning of crop residues is completely eliminated, which also contributes to a reduction in greenhouse gas release. Soils under zero tillage – depending on the type of management – might also emit less nitrous oxide (Izaurralde *et al.*, 2004). With paddy rice in particular, the change to zero tillage systems combined with adequate water management can positively influence the release of other greenhouse gases, such as methane and nitrous oxides (Belder 2005; Gao 2006).

CONSERVATION AGRICULTURE IN RICE-BASED CROPPING SYSTEMS

Irrigated paddy rice has for a long time been considered a stable and sustainable cropping system, although it is far from being conservation agriculture (the puddling results in the destruction of the soil structure). However, irrigated rice is increasingly subject to pressures:

- The high fuel costs of puddling and the reduced availability of labour mean that there is pressure to change from transplanted to direct-seeded rice.
- The water consumption of traditionally puddled rice is too high in many regions – alternatives must be found and rice growing is already restricted in some areas: cultivation of summer rice, grown prior to the monsoon season, is not allowed in parts of northern India; in Karakalpakstan, adjacent to the Aral Sea in Uzbekistan, rice cultivation is restricted because of the scarce water resources and the high evaporation losses; in China, the paddy rice areas around the city of Beijing have been replaced by other crops due to the alarming fall in the ground-water table.
- The release of greenhouse gases such as methane is high in traditionally flooded rice (Gao, 2006).

Rice cultivation has therefore been adapted to conservation agriculture in several countries. Rice can be cultivated without puddling or permanent flooding by adopting resource-conserving technologies. FAO has been working on rice-based CA systems in China and the Democratic People's Republic of Korea, while in the Indo-Gangetic Plains the Rice-Wheat Consortium has been successfully introducing RCTs into rice-based cropping systems. Neither puddling nor zero tillage in rice result in higher yields of the non-rice crops in the crop rotations. The reported water saving through RCTs is usually higher in paddy rice than in other rotation crops (PDCSR, 2005). Cropping systems involving residue retention and zero tillage perform better in terms of profitability, yields and resource conservation, while conventional systems and zero tillage systems without residue retention are inferior. In addition to the resource-conserving effects, the cropping systems involving permanent zero tillage, so-called "double zero tillage"[2]

[2] Term used in rice-wheat cropping in South Asia to describe a system where both, rice and wheat, are cropped under zero tillage.

and residue retention result in significantly increased water infiltration rates (PDCSR, 2005).

The experiences and results obtained in CA in other cropping systems can be confirmed for rice-based cropping systems. This includes options for mitigating climate change by sequestering carbon in the soil and reducing the emission of other greenhouse gases (Gao, 2006). The Rice-Wheat Consortium has developed technologies which allow the application of conservation agriculture in rice-based cropping systems (RWC-CIMMYT, 2003): laser levelling, permanent bed planting and the retention of residues (including rice straw). In rice-wheat systems, the introduction of sesbania as a cover crop to bridge the gap between the wheat harvest and rice seeding is well accepted by the farming community. It helps with weed control and adds additional nitrogen and organic matter to the system. Direct seeding equipment has been developed and introduced to the market to seed different crops into residues and under zero tillage either on flat fields or raised beds (PAU, 2006). The latest model of the "Turbo Happy Seeder" can even cope with seeding into fresh rice straw (Dasmesh, 2006).

CONCLUSIONS

Resource-conserving technologies applied in isolation have advantages and disadvantages; they are not universally applicable as the problems can sometimes outweigh the benefits. However, by combining different resource-conserving technologies, synergies can be created to eliminate the disadvantages of single technologies and accumulate the benefits.

Different RCTs are successfully applied under the concept of conservation agriculture in different cropping systems around the world, allowing stable agricultural production without the known negative environmental impact. The Rice-Wheat Consortium of the Indo-Gangetic plains has been instrumental in adapting the concept of conservation agriculture to rice-based cropping systems, resulting in higher yields, greater profitability, enhanced soil fertility and better water-use efficiency – it represents a possible route towards sustainable agricultural production in rice-based systems. High water consumption is a particular concern. In regions where cropping mainly depends on groundwater for irrigation purposes and where the groundwater tables are falling dramatically, such as in the Punjab of India, water-saving technologies might not be sufficient to guarantee sustainability of the cropping systems. The combination of different RCTs – such as mulching, direct seeding and double zero tillage – results not only in water saving but also in increased infiltration rates (and hence the recharge of the aquifer during the monsoon season).

Combined resource-conserving technologies applied in conservation agriculture produce benefits for the farming sector, the environment and the general public, and it is therefore important to promote and adopt them. FAO and regional partners, such as the Rice-Wheat Consortium, can play an important role in this process.

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Agriculture de conservation: synergies entre technologies de conservation des ressources dans les systèmes de production à base de riz

L'Agriculture de conservation (AC) se définit comme un concept visant à un type de production agricole économe en ressources de base, tout en gardant une rentabilité acceptable et un niveau de production à la fois élevé et durable, le tout dans le respect de l'environnement. L'AC a pour principe de base l'intensification des processus biologiques, tant au dessus de la surface du sol qu'en dessous. Les interventions telles que le labour physique du sol sont maintenues à un minimum absolu, et le recours aux intrants extérieurs tels que produits agrochimiques et nutriments d'origine minérale ou biologique est optimisé, de façon à respecter les processus biologiques sans leur opposer d'obstacle ou de contrainte. L'AC se caractérise par trois principes liés entre eux:

1. Un minimum de bouleversement mécanique du sol tout au long du cycle cultural.
2. La permanence d'un couvert organique du sol.
3. Rotations de cultures diversifiées dans le cas des cultures annuelles, et associations de cultures diversifiées en cas de cultures pérennes.

Les façons culturales traditionnelles en riziculture font appel à un travail du sol intensif à l'occasion de la mise en boue – ce qui n'est pas compatible avec le concept de l'AC. Cependant, la riziculture peut s'adapter aux principes de l'AC tels qu'ils sont mis en œuvre de façon de plus en plus courante. Outre les avantages qu'on lui connaît déjà, l'application de l'AC à la riziculture conduirait également à une économie d'eau (une ressource de plus en plus rare) et contribuerait à la solution du problème des émissions de gaz d'effet de serre à partir des rizières – sans pour autant compromettre le potentiel de production. Le document explique le concept et les principes de l'AC et examine l'étendue de son expansion actuelle à travers le monde. On y trouvera des exemples factuels d'introduction de l'AC dans des systèmes de production agricole basés sur le riz, et une vue générale de ses avantages, tant déjà démontrés qu'attendus à l'avenir.

Agricultura de conservación: sinergias de las tecnologías de conservación de los recursos en los sistemas basados en el arroz

La agricultura de conservación se define como un concepto de producción agrícola con ahorro de recursos que procura obtener ganancias aceptables y niveles de producción elevados y constantes y asegurar, al mismo tiempo, la conservación del medio ambiente. Este enfoque se basa en la potenciación de los procesos biológicos naturales, tanto por encima como por debajo del suelo. En la agricultura de conservación se reducen lo más posible intervenciones como la labranza mecánica del suelo, mientras que insumos externos tales como agroquímicos y nutrientes de origen mineral u orgánico se aplican en la cantidad óptima para no interferir con los procesos biológicos ni perturbarlos. Tres principios relacionados entre sí caracterizan la agricultura de conservación:

1. Perturbación mecánica del suelo reducida al mínimo en todo el ámbito de la rotación de cultivos.
2. Cubierta orgánica permanente del suelo.
3. Rotación diversificada de cultivos en el caso de los cultivos anuales, o asociación de plantas en el de los perennes.

Las prácticas tradicionales empleadas en los arrozales se basan en la labranza intensiva del suelo durante el enfangado, lo cual no es compatible con los principios de la agricultura de conservación. Sin embargo, es posible adaptar el cultivo de arroz a estos principios, cuya aplicación está cada vez más difundida. Además de sus reconocidas ventajas, en el caso del arroz la agricultura de conservación también permitiría ahorrar agua (un recurso que escasea cada vez más) y ayudaría a hacer frente al problema de las emisiones de gases de invernadero procedentes de los arrozales sin sacrificar su potencial productivo. El documento explica el concepto y los principios de la agricultura de conservación y el alcance de su aplicación actual en todo el mundo, proporciona ejemplos de su introducción en sistemas de cultivo basados en el arroz, y traza un cuadro de sus ventajas probadas y previstas.

Energy generation from rice residues – a review of technological options, opportunities and challenges

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INTRODUCTION

Reliable and adequate supplies of energy are a fundamental necessity for economic growth and development of any community or country. This paper presents technological aspects of the extraction and utilization of energy from rice straw and rice husks. Drawing from case studies of major rice-producing countries in Asia and Africa, it discusses constraints militating against the application of these technologies in rural areas in developing countries and presents possible areas for intervention by various stakeholders.

TECHNOLOGIES FOR ENERGY PRODUCTION FROM RICE RESIDUES

Properties of importance in energy generation

Rice straw and rice husk are lignocellulosic materials with a low bulk density and a relatively high silica content. The main chemical components on a dry basis are cellulose, hemicelluloses, lignin and ash. Lignin is found in the middle lamella and adjacent primary cell walls of the residue tissue, and as such it encapsulates the cellulose and hemicellulose fractions found primarily in the secondary cell walls. Rice straw and husk have relatively high proportions of silica-rich ash. Table 1 presents the main physical properties and chemical composition data that are important in the use of rice straw and rice husks as feedstock for energy generation. Data are also presented on a selection of other biomass fuels for comparison. The implications of these properties for energy generation processes are discussed herein.

Steps in the energy conversion chain

The chain of operations involved in obtaining energy from rice residues comprises the following five steps:

- collection, handling and delivery to a pre-treatment site;
- pre-treatment to prepare the biomass for subsequent conversion;
- conversion of the residue to fuel;
- refining of the fuel; and
- conversion of the fuel into usable energy.

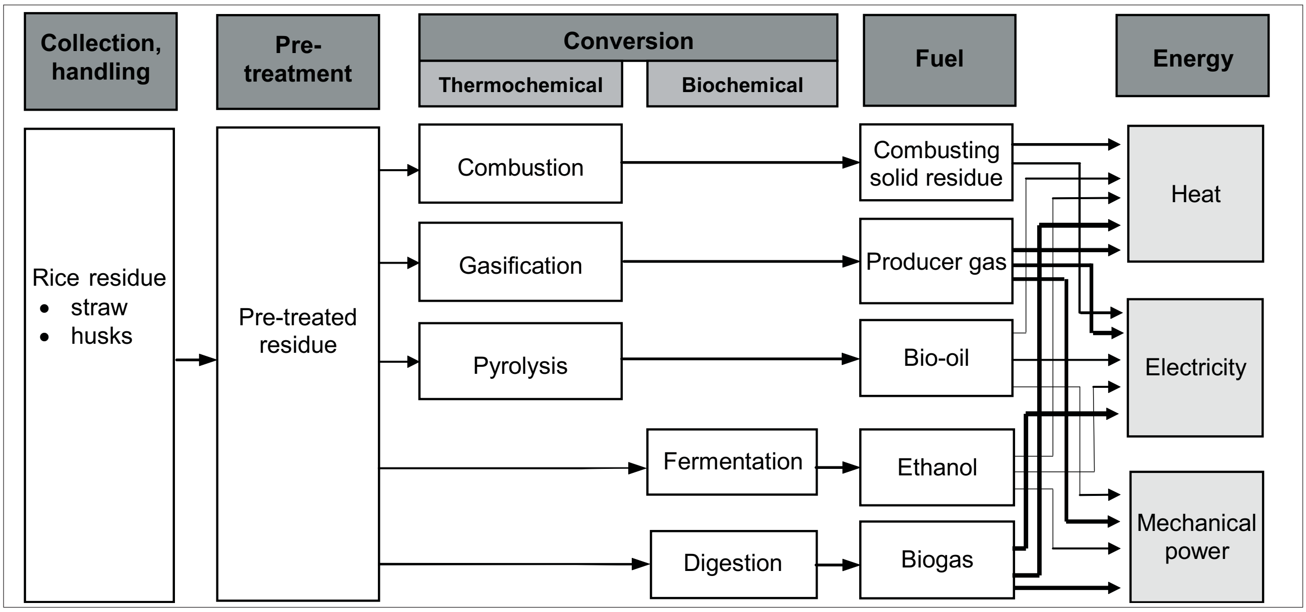
The conversion technology applied dictates the pathway taken to implement each of the five steps in the

TABLE 1
Physical properties and chemical composition of rice residues and other biomass

	Rice straw	Rice husk	Sugar cane bagasse	Eucalyptus wood	Cattle manure
Moisture content (%)	7–13	10–13	48	52	78
Bulk density (*kg/m*^{3})	60	130	160	500	
Chemical composition (%)					
cellulose	35	47	41	43	
hemicellulose	35	18	24	35	
lignin	6	13	18	22	
Carbon-nitrogen ratio	53	102	118	160	18
Ash content (*% of dry matter*)	19	20	2–5	<1	
Silica content of ash (%)	75	91	47		
Residue-to-crop ratio[a] (*kg/kg*)	1.25	0.25	0.29		

[a] For rice straw and rice husk the crop refers to de-husked unpolished grain

FIGURE 1
Pathways for producing energy from rice residues



Source: Bridgwater, 2006 (adapted).

chain (Figure 1). However, irrespective of which pathway is taken, the principal technological challenge that must be faced is to cost-effectively achieve an optimal net positive energy balance for the chain while minimizing the negative effects on the environment and fostering the economic and social development of local communities. As energy – mostly provided by fossil fuels – is required to carry out operations in the chain, an appropriate technology package is required involving minimal energy input (in order to maintain a positive energy balance) and resulting in minimal emission of greenhouse gases and other atmospheric pollutants.

Collection and handling of rice residues

Residues are collected, handled and transported to the site where subsequent operations are carried out. For each kilogram of rice grain, 0.25 kg of husks and 1.25 kg of straw residues are generated (Table 1). Husks are found in high concentrations at the mill where dehusking takes place and can therefore be readily collected and used for energy generation to power various mill operations. In comparison, straw is usually strewn over wide areas in harvested fields and may require substantial inputs of energy – often from fossil fuels – for baling, temporary storage, drying and transportation to the pre-treatment or conversion site.

Pre-treatment

Pre-treatment turns residues into a form that facilitates handling, improves efficiency and limits the adverse environmental impacts of conversion processes. The main pre-treatment steps are described below:

- **Drying** may be done naturally – sun-drying – or by artificial means in an appropriately designed drier.
- **Size reduction** processes (e.g. chopping and maceration) increase the surface area available for, and hence the rate of, biochemical conversion reactions.
- Given the high resistance of lignin to biodegradation, **delignification** is required to expose the cellulose and hemicellulose fractions to biochemical conversion reactions. One method is to steep in an alkali (e.g. sodium hydroxide) and then wash with water (Barreveld, 1989; Marchaim, 1992).
- **Densification** is applied to residues intended for direct combustion and gasification. It improves combustion characteristics, increasing the conversion efficiency and reducing environmental pollutants. It facilitates the handling, transportation and storage of residues. Rice straw can be densified by baling during collection, or by size reduction followed by briquetting; rice husks can be densified by briquetting, after (or without) prior size reduction (Beagle, 1978; Grover and Mishra, 1996; Assureira, 2002).

Conversion

Several technologies exist for converting rice residues into usable energy, including: thermochemical conversion through direct combustion, gasification and fast pyrolysis; and biochemical conversion through anaerobic digestion and fermentation (Figure 1).

Thermochemical conversion processes

Direct combustion. Heat energy is produced during combustion of rice straw or rice husks in stoves, furnaces and kilns. These devices must be properly designed to ensure proper operation, optimal conversion efficiency and heat efficiency. The feeding system must be designed to meter residue at an optimal rate into the combustion chamber. Densification into pellets (see above) improves the handling and combustion characteristics of residues. Rice residues have a high ash content and provision must be made to evacuate ash as fast as it forms in order not to impede the airflow into the combustion area. The design and maintenance plan must take into account the fact that the heat transfer efficiency will be decreased by ash deposits on the combustion chamber walls and that, due to its high silica content, ash is very abrasive and corrosive of metals (FAO, 1993; Robinson, Hollingdale and Reupke,1993; Himpe, 1997; Badger, 1999).

Gasification. Gasification is the thermal conversion of rice straw and rice husk into producer gas (a combustible mixture of carbon monoxide, hydrogen, methane, nitrogen and carbon dioxide). Compared with direct combustion, gasification gives greater flexibility in the use of the fuel and higher conversion efficiency (Stout 1989; FAO, 1999). A residue of ash is formed in the process, and so the design of the combustion chamber is as for direct combustion.

Fast pyrolysis (bio-oil production). Bio-oil is a type of liquid fuel formed through the condensation of gases generated by the decomposition of rice residues by fast pyrolysis. It is a complex mixture of hydrocarbons, phenolic materials and water – the latter acts as a diluent to maintain homogeneity and optimal viscosity. Fast pyrolysis is an advanced process with carefully controlled parameters ensuring high heat transfer rates to the feedstock; a crucial pre-treatment step is size reduction of the residue to very finely divided pieces. Fast pyrolysis for conversion of biomass to organic liquids in high yields became a technical reality 25 years ago (Scott and Legge, 1999; Bridgwater, 2006).

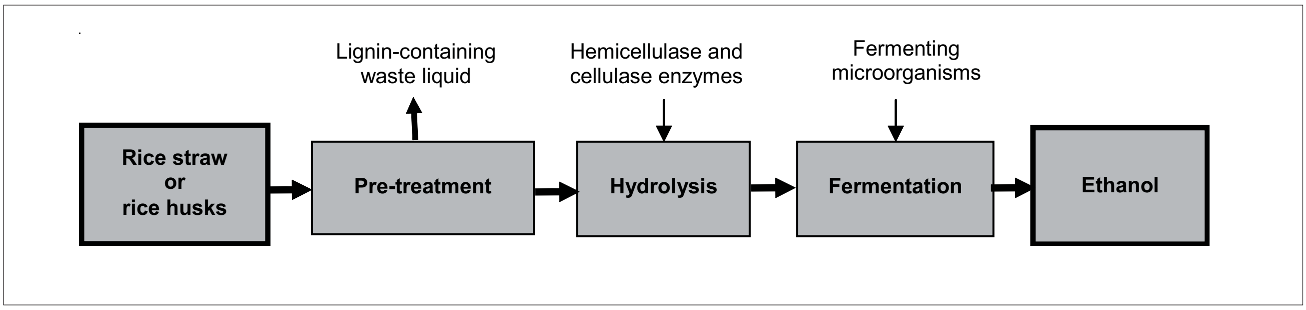
Biochemical conversion processes

Fermentation (ethanol production). Biochemical conversion processes require two main pre-processing operations – size reduction and delignification (see above). Following these operations, the production of ethanol from rice residues involves two main steps: enzymatic hydrolysis of cellulose and hemicellulose into simple hexose and pentose sugars, and fermentation of simple sugars into ethanol (Figure 2).

In recent years there has been a marked acceleration in the development of economically feasible technologies for lignocellulosic ethanol production. These technologies are now commercialized and numerous commercial plants are being developed in the United States, Canada, Brazil, Europe and Japan (Miyamoto, 1997; Solomon, Barnes and Halvorsen, 2007; Yang and Lu, 2007).

Anaerobic digestion. Anaerobic digestion of biomass in semi-continuous digesters is one of the bioenergy generation technologies that have been applied successfully in small-scale operations in rural areas of developing

FIGURE 2
Steps in ethanol production from rice residues



countries. Anaerobic digestion generates biogas, a gaseous mixture of methane, carbon dioxide, hydrogen with small quantities of carbon monoxide, oxygen and hydrogen sulphide. A carbon-to-nitrogen ratio of around 30 is the threshold above which it is considered that the quantity of nitrogen available in the digestion feedstock may be insufficient to support the metabolic processes of the microbiological populations involved. With carbon-to-nitrogen ratios that exceed this value by far (Table 1), rice residues are unsuitable as anaerobic digestion feed-stock; however, they may be used if the nitrogen content is raised by mixing with appropriate nitrogen-rich materials (e.g. animal manure, night soil and ammonia). Ammonia also has a delignification effect on ligno-cellulosic materials, and ammoniation may therefore be carried out to achieve both delignification and nitrogen-content adjustment of rice residues. The fibrous nature of rice residues may pose a problem, as residues tend to float and form a hard scum on the surface of digester contents; in this case, special measures must be taken – maceration of the slurry before feeding into the digester and intermittent or continuous mechanical mixing during digestion (Barreveld, 1989; Marchaim, 1992).

Energy utilization

Fuels obtained from rice residues can provide energy in various forms: heat, motive power and electricity (Figure 1). Table 2 shows the energy content of rice residue fuels and data for other comparable fuel products.

Heat

Heat energy produced during direct combustion of rice residues can be used for domestic cooking and heating, as well as for providing process heat in small- and medium-scale industrial operations (e.g. rice parboiling and drying, tobacco curing, bricks and ceramics production, pottery etc.). It is also possible to generate heat by burning liquid fuels (bio-oil and ethanol) and gaseous fuels (producer gas and biogas) derived from residues (Figure 1). Heat generated through direct combustion of residues, or through burning liquid and gaseous derivative fuels, can be used to generate boiler steam to provide heat for use in domestic or industrial operations.

Mechanical power

Gaseous fuels (biogas and producer gas) and liquid fuels (bio-oil and ethanol) obtained from rice residues can be used in internal combustion engines to provide shaft power for pumps, crop processing machinery (e.g. dryer fans and grain threshers), refrigeration systems and other devices in rural areas.

Liquid fuels offer the advantage of easy storage and transportation, and are therefore more suitable than gaseous fuels for powering vehicles and mobile equipment. Unlike ethanol, bio-oil does not mix easily with conventional fossil fuels and has to substitute, rather than be blended with, gasoline or diesel fuel in engines.

Producer gas and biogas are cleaned by bubbling through scrubbers and filters before being used in engines. Both gases contain high proportions of carbon dioxide which is incombustible. Biogas also contains hydrogen sulphide – a corrosive substance that increases engine wear and burns to form sulphur dioxide, itself corrosive and a contributor to acid rain. During gasification, tars and particulates (ash and char) get entrained in the resulting producer gas. They cause damage to engines and lead to environmental pollution (FAO, 1990; Marchaim, 1992; Jenkins, 1999; FAO, 1999; Wheeler, 2000).

Electricity

There are three ways of obtaining electrical power using rice residues as energy feedstock:

TABLE 2
Heating value of rice residue fuels and other comparable fuels

Solid fuels	Heating value (*MJ/kg dry matter*)	Liquid fuels	Heating value (*MJ/kg*)	Gaseous fuels	Heating value (MJ/m^3)
Rice straw	15.32	Bio-oil	17.00	Producer gas	5.90
Rice husk	15.25	Ethanol	26.80	Biogas	20–29
Eucalyptus wood	18.00	Gasoline	44.37	Methane	38.00
Sugar cane bagasse	16.22				
Coal	30.20				

- Gaseous or liquid fuel derivates can be used to run an internal combustion engine providing shaft power to an electricity generator.
- Gaseous fuel derivatives can be used in a gas turbine running an electricity generator.
- Steam generated in a boiler (see above) can be used to operate a turbine that in turn runs an electricity generator.

Electricity generated using any of these three methods can be used in decentralized or grid-connected systems for domestic or industrial applications.

Combined heat and power (CHP)

Rice residues can be used in CHP (cogeneration) systems to simultaneously generate heat and electricity by using either flue gases from electricity-generating gas turbines or waste steam from electricity-generating steam turbines to provide heat for industrial or domestic use. Cogeneration systems are in wide use in rice processing plants, where rice husk from milling is used in boiler furnaces for raising steam which is in turn used for generating electricity to power milling operations. The steam which exits the steam turbine is used to provide process heat for drying and parboiling operations.

Utilization of by-products

The commercial utilization of by-products formed in the bioenergy chain increases the economic feasibility and commercial viability of systems for generating energy from rice residues.

Direct combustion and gasification

A substantial quantity of ash is generated as a by-product during direct combustion and gasification. The ash is rich in silica (Table 1), is highly porous and has a very high surface area. It is a good heat insulator and is therefore suitable for incorporation in refractory bricks and for ensuring uniform cooling and solidification of steel. It can also be used as a fertilizer, oil absorbent, anti-caking agent, filter medium, filler in rubber components, additive in cement and as a source of silica for industrial operations such as glass making (Beagle, 1978; Robinson, Hollingdale and Reupke, 1993).

Anaerobic digestion

The effluent from semi-continuous anaerobic digesters can be used in soil fertility improvement and conditioning, as well as in animal feed and fishmeal (Marchaim, 1992; Wheeler; 2000).

Cellulosic ethanol production

The main by-product from ethanol production is lignin from delignification (Figure 2). With a heating value of 26.63 MJ/kg, lignin is a bona fide fuel material that can be used to provide industrial process heat. Lignin can also be used as raw material for producing a variety of high-value chemicals such as phenols (Scott and Legge, 1999; Bridgwater, 2006).

Bio-oil production

Non-condensable gases and the char residue formed during the fast pyrolysis of rice residues can be used as stand-alone fuels to provide heat in various industrial operations (Scott and Legge, 1999; Bridgwater, 2006).

OVERCOMING CONSTRAINTS IN THE USE OF RICE RESIDUES

The various constraints to the adoption and use of technologies for converting rice residues and other agricultural biomass into energy in rural areas in developing countries are outlined below and the action to be taken by various stakeholders is highlighted (Woods and Hall, 1994; FAO, 1997; Kartha and Larson, 2000; Leung, Yin and Wu, 2004; FAO, 2005; von Braun and Pachauri, 2006; Ahiduzzaman, 2007). Case examples from Asia and Africa are then presented.

Constraints and possible interventions

Policies and institutional framework

In many countries there are no policies providing an environment conducive to the successful development and operation of energy technologies based on biomass in general and rice residues in particular.

Governments must formulate policies and programmes for the bio-energy sector, as part of wider strategic plans for economic development and improvement of living standards in rural areas. Such policies should take into account the multifaceted nature of residue energy production and utilization, with consideration for the technical, economic and socials aspects.

A framework of relevant institutions is required to support residue energy systems. The framework should involve all government ministries and public institutions dealing with the relevant sectors (i.e. agriculture, energy, rural development, environment, planning, industrial development, public works, infrastructure etc.). It should also have links with relevant private sector partner institutions, including financial institutions, advisory services, NGOs, community organizations and utility companies. The policy and institutional framework must develop and enforce rules and regulations for: guiding production, marketing and utilization of energy; providing criteria for quality grades and standards; minimizing negative environmental and health impacts; and applying various pricing instruments and incentives such as subsidies and taxes. International organizations have an important role in providing financial and technical assistance in the development of institutional frameworks, strategies, policies and programmes.

Infrastructure

Many countries lack the infrastructure base required to support the development and utilization of bioenergy technologies.

Governments (local and national) are responsible for providing the infrastructure and infrastructure services that are public goods, and they must also provide the necessary environment and incentives for private sector investment in other infrastructures (residue storage structures, fuel storage structures, pipelines etc.).

Where feasible, local communities should be involved in the construction and maintenance of infrastructure, for example, laying pipe networks to distribute biogas from community digesters to homes. Assistance from international agencies is required to undertake the analysis of infrastructure needs, identify suitable infrastructure and operational models, mobilize required financial resources, develop and implement guidelines and standards at international level, and provide technical and financial assistance in infrastructure development programmes.

Awareness, data and information

There is a lack of awareness of the various aspects of energy generation from rice residues among feedstock producers, technical support personnel, researchers, private sector individuals, policy-makers and energy users. They are not familiar with the technical options for energy generation or the advantages compared to conventional fuels, and they are unaware of the opportunities for job creation and income generation, as well as the social and environmental implications. When people are aware, they are nevertheless without reliable and accurate information concerning critical elements such as potential resources, energy demand, energy utilization and related socio-economic factors.

Governments and private sector stakeholders should carry out awareness-raising campaigns and pilot demonstration projects; they should take appropriate action to generate the data necessary for technology selection and design, policy formulation and development planning. In addition, they should disseminate information dealing with residue utilization, using the available media (printed bulletins and newsletters, radio, television, Internet etc.) and targeting specific interest groups or the public at large.

Through normative (and other) studies, international organizations need to generate relevant data and information; they should also carry out activities within programmes and projects to facilitate access to information and strengthen information exchange networks.

Capital

A very important factor inhibiting the widespread adoption of residue transformation and utilization technologies in rural areas is the lack of capital to cover investment and operations costs.

Measures are required to improve the access of rural dwellers, community groups, potential business people and micro-enterprises to credit and finance schemes that are suitable for local conditions. Governments need to set up an institutional framework and incentives (e.g. low interest or subsidized loans) in order to encourage investment by the private sector. International organizations should provide assistance in developing appropriate institutional frameworks and microcredit schemes.

Skills

The adoption and application of technologies required is hindered by the low level of technical and business management skills and lack of organizational capacities in rural areas. The people who plan the development of bioenergy systems and those that provide technical support for operating these systems often lack the necessary technical and managerial skills.

Training programmes should be organized by governments and the private sector to impart the required skills to policy-makers and planners, and to develop a critical mass of technical personnel familiar with the technologies. Training programmes are required to target relevant rural dwellers, community groups and micro-enterprises and to cover the basic technical aspects, small business management and marketing. International organizations can provide financial and technical assistance in projects with components related to training and demonstration.

Technology

Affordable, easy-to-operate, economically viable, socially acceptable and environmentally friendly technologies adapted to local conditions are required for the production and utilization of energy from rice residues. Basic and applied research is needed to develop new technologies or adapt existing ones to local conditions. Research is required with regard to the technical aspects (e.g. improving conversion efficiency), environmental impacts and socio-economic implications of technology packages, and an appropriate institutional framework must be put in place to support the research, development and demonstration of technologies. The private sector is central to technology development: it carries out its own investigations, provides grants for research and collaborates with research and teaching institutions in their activities. International agencies can provide technical and financial assistance to facilitate technology and knowledge transfer and to strengthen national capacity in assessing, developing and adapting technologies.

Case example 1: Improved rice husk furnace for rice parboiling in Bangladesh

Biomass is by far the dominant energy source in Bangladesh, accounting for approximately 67 percent of the country's total energy consumption. A survey of rice mills revealed that an average 187 kg of husks are produced per tonne of paddy and 70 percent of husks are consumed by the mills themselves for energy generation. Traditionally, mills use poorly designed furnaces to power boilers, leading to poor thermal efficiency and high pollution. Carbon monoxide levels in exhaust gases are double the threshold established by the Ministry of Environment and Forestry.

Collaboration between the Bangladesh Rice Research Institute and the Natural Resources Institute (United Kingdom) led to the design of an improved system featuring: better thermal efficiency, improved fuel conversion efficiency, shorter parboiling time, and a level of carbon monoxide in the flue gas well within legally permitted limits. Studies carried out by a national research organization and technical assistance provided by a development agency were instrumental in the development of an economically viable and environmentally sustainable rice residue conversion technology (Ahiduzzaman, 2007 – based on).

Case example 2: Setting policy in Viet Nam

In 2003, Viet Nam passed a decree (Prime Minister's Decree No.102/2003/ND-CP) to guide the rational exploitation of energy resources in meeting the growing energy demands of the national economy while protecting the environment and achieving sustainable socio-economic development. The decree outlined the legal instruments (e.g. tax preferences) for the importation of energy-saving technologies, and directed ministries and other public sector agencies to allocate funding for scientific, technological and environment research targeting the efficient use of energy. The decree also required these agencies to disseminate relevant information using the mass media and to carry out awareness-raising activities (The National Legal Database, 2003).

Case example 3: Incentives for cellulosic alcohol in China

China imports close to 43 percent of its petroleum requirements and in 2005 petroleum imports increased to about 865 million barrels. In order to reduce dependence on imports, the Government is taking measures to promote the use of ethanol as a petroleum substitute. Given the food security implications of obtaining ethanol from corn, cellulosic ethanol was identified as a more viable substitute for petroleum than corn alcohol.

In 2005, cellulosic ethanol was selected as one of the key environmental protection and energy development technologies to receive priority support under the national strategic high-technology research and development programme. In order to attract foreign technology and capital, the Government recently announced plans to invest US$ 5 billion over the next 10 years in ethanol capacity expansion with a focus on cellulosic ethanol (Yang and Lu, 2007 – based on).

Case example 4: Technical assistance by FAO in Egypt

Through imaginative agronomic programmes and technical assistance to growers, Egypt's rice production systems have become some of the highest-yielding in the world. While high yields have secured the availability of rice grain for feeding the population and earning foreign exchange, large quantities of residue are generated, constituting a major disposal problem. Almost 2 million tonnes of rice straw are burned on-farm resulting in greenhouse gas emissions, aerial pollution and the loss of potential revenue that could be generated from processes using straw as raw material.

In December 2006, FAO started a 20-month pilot technical cooperation project (TCP) in the Nile Delta; one of the key specific objectives is to analyse the technical and economic feasibility of using rice straw as feedstock for energy generation, and findings will be used to design strategies within a proposal for a follow-up project. This is an example of how an international organization can successfully provide technical and financial assistance to support studies, information generation and the design of future interventions in a national programme.

CONCLUSION

Rice residues have immense potential as an energy source in rural areas of developing countries. Technologies applied in the conversion and utilization chain should result in favourable carbon and energy balances and in minimal particulate and greenhouse gas emissions. To overcome the constraints to the adoption and use of these technologies in rural areas, action is required by the public sector, the private sector, local communities, development agencies and international organizations. An appropriate policy, institutional and regulatory framework is needed to create an environment that is conducive to the development and operation of these technologies. Awareness needs to be raised about energy generation from rice residues, while access to capital and relevant information needs to be facilitated. The technical and managerial capacity of various stakeholders needs to be strengthened, and support has to be provided for research, development and demonstration of low-cost technologies appropriate for the particular locality.

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Production d’énergie à partir des résidus de la riziculture – un inventaire des options technologiques, des opportunités et des obstacles à surmonter

Un approvisionnement fiable et suffisant en énergie est une condition fondamentale de la croissance économique et du développement d’un pays ou d’une communauté. L’utilisation domestique de l’énergie couvre la cuisine, l’éclairage et le chauffage; l’agriculture quant à elle en a besoin pour actionner les machines agricoles; tandis que la totalité des secteurs industriels qui traitent des matières premières jusqu’au stade du produit fini utilisent de l’énergie sous une forme ou sous une autre. La disponibilité d’énergie est un facteur important de la création d’emplois et de services dans le domaine de la santé, de l’éducation et de l’assainissement, et constitue en conséquence un facteur clé de l’amélioration du niveau de vie.

Le recours aux carburants d’origine fossile pour la production d’énergie constitue un problème pour la durabilité du développement rural dans les pays en voie de développement. Le plus souvent, ces carburants sont importés et leur utilisation compromet la sécurité énergétique du pays. Les prix des carburants pétroliers sont liés à la conjoncture géopolitique et tendent en conséquence à être imprévisibles, outre leur niveau trop élevé pour une grande partie de la population. La combustion des carburants fossiles relâche dans l’atmosphère du dioxyde de carbone et autres gaz d’effet de serre, sans compter les produits polluants à l’origine de smog, d’intoxications au plomb, de pluies acides et de divers autres problèmes localisés de qualité de l’air.

La production d’énergie à partir de résidus végétaux est une option économiquement viable dans les pays en voie de développement, où les résidus végétaux sont généralement abondants tant en raison de la production agricole que des activités de transformation de ses produits. Les résidus végétaux sont renouvelables à un horizon temporel relativement rapproché, et leur influence sur le cycle du carbone tend à être moins marquée que celle des carburants fossiles. De plus, l’utilisation de résidus végétaux pour la production d’énergie limite la déforestation induite par la production non durable de charbon de bois et de bois de feu. Contrairement à la mise en culture de plantes destinées à la production d’énergie, l’utilisation énergétique de résidus végétaux ne conduit pas à des conflits sur l'utilisation des ressources foncières, et le risque est moindre – par comparaison avec la production de bioéthanol à partir de canne à sucre ou de maïs, et de biodiesel à partir d'oléagineux – d'assister à un impact négatif sur la disponibilité de nourriture. Les industries basées sur la valorisation énergétique des résidus végétaux sont une source potentielle d'emploi rural.

Les options technologiques retenues pour la production d'énergie à partir de résidus végétaux doivent être concurrentielles en termes économiques, mais également rester compatibles avec la durabilité environnementale et apporter un plus au développement économique et social des communautés locales. Les carburants produits doivent, pour se faire accepter et utiliser à grande échelle, avoir un prix abordable et une qualité irréprochable, tout en présentant une souplesse d'utilisation convenable.

Le présent document examine les aspects technologiques de l'extraction et de l'utilisation d'énergie à partir des pailles et des balles de riz. Sur la base d'études de cas portant sur les principaux pays producteurs d'Asie et d'Afrique, les contraintes qui s'opposent à l'adoption de ces techniques sont passées en revue, et des possibilités d'intervention par diverses parties prenantes sont développées.

Generar energía a partir de residuos de arroz Un examen de las opciones tecnológicas y de las oportunidades y desafíos que se plantean

Un suministro fiable y adecuado de energía es fundamental para el crecimiento económico y para el desarrollo de toda comunidad o país. Los usos domésticos de la energía comprenden su empleo para cocinar así como para calefacción e iluminación; en el campo se necesita energía para accionar la maquinaria agrícola; por último, todas las actividades industriales requieren una u otra forma de energía para convertir la materia prima en su producto final. La disponibilidad de energía es un factor importante para proporcionar empleo, asistencia médica, educación y saneamiento; se trata, pues, de un elemento esencial para la mejora de los medios de vida.

El suministro de energía a partir de combustibles fósiles entraña problemas para el desarrollo sostenible de las zonas rurales en los países en desarrollo. Esos combustibles muy a menudo son importados, lo cual compromete la seguridad energética del país. Los precios de los combustibles derivados del petróleo están vinculados a los acontecimientos políticos mundiales y, por consiguiente, son difíciles de predecir, además de no ser asequibles para una parte considerable de la población. Por otra parte, su combustión libera dióxido de carbono y otros gases de efecto invernadero, así como sustancias que forman nieblas contaminantes y provocan fenómenos de toxicidad, depósitos de ácidos y varios otros problemas locales relacionados con la calidad del aire.

La producción de energía a partir de residuos vegetales representa una opción viable en las zonas rurales de los países en desarrollo, donde habitualmente es posible encontrar gran cantidad de residuos de la producción de cultivos y las actividades de elaboración agrícola. Los residuos vegetales son renovables en un tiempo relativamente breve y tienden, en comparación con los combustibles fósiles, a tener un efecto más neutro respecto de las emisiones de carbono. Además, el uso de residuos vegetales para generar energía reduce la práctica no sostenible de la deforestación con miras a producir leña y carbón vegetal. A diferencia de la producción de cultivos energéticos, el suministro de energía a partir de residuos evita el conflicto con otras formas de uso de la tierra. Además, con respecto a la obtención de bioalcohol del maíz y la caña de azúcar, o a la producción de biodiésel a partir de oleaginosas, tiene menos probabilidades de influir negativamente en la disponibilidad de alimentos. Las industrias que se basan en la producción de energía a partir de residuos vegetales constituyen una posible fuente de generación de empleo en las zonas rurales.

Las opciones tecnológicas que se elijan para esta producción energética deben ser competitivas desde el punto de vista económico, pero a la vez compatibles con la sostenibilidad ambiental; deben, además, fomentar el desarrollo económico y social de las comunidades locales. Para ganarse una aceptabilidad y una utilización amplias los combustibles deben tener precios abordables y ser de calidad óptima, y deben dar lugar a una utilización flexible.

En este documento se examinan los aspectos tecnológicos de la extracción de energía de la paja y los hollejos de arroz, así como el uso de dicha energía. Sobre la base de estudios de caso relativos a importantes países productores de arroz de Asia y África se examinan los obstáculos que se oponen a la aplicación de estas tecnologías, y se presentan las posibles esferas de intervención de los distintos grupos interesados.

Weed management in European rice fields

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INTRODUCTION

Rice is cultivated in the European Union on submerged land in the coastal plains, deltas and river basins, covering a total area of about 400 000 ha, all in the Mediterranean countries. The average crop yields are between 4.80 and 7.25 tonnes/ha, depending on the environmental conditions and water availability. Milled rice consumption ranges from about 6.0–7.0 kg/caput (17 kg/caput in Portugal) in the Mediterranean areas, where the crop is traditionally grown, to 3.5–5.3 kg/caput in non-rice-producing countries (Ferrero, 2005). In Europe's rice-producing countries, most of the rice consumed is from *japonica* varieties, while in northern countries mostly *indica* varieties are consumed.

The ecological conditions of rice cultivation vary with climates ranging from temperate to subtropical (Nguyen and Ferrero, 2006). At higher latitudes (Italy, northern Spain, France) rainfall is concentrated during the first stages of the crop (April–June) and during the harvesting period. Average temperatures in these areas range from 10°–12°C during crop germination to 20°–25°C at flowering time.

Rice is mostly grown on fine-textured, poorly drained soils, where the pH is between 4 and 8 and organic matter between 0.5 and 10 percent. In coastal areas, soils are frequently saline or very saline. Most of the irrigation water is obtained from rivers (Po in Italy, Ebro and Guadalquivir in Spain, Tejo in Portugal, Axios in Greece etc.) and lakes. In European areas, rice is mostly cultivated under permanent flooding, adopting mainly the "flow-through" system, with short periods during which the soil is dried to favour rice rooting (in the early stages) or weed control treatments. Water is kept at a level ranging from 5 cm (in the early stages) to 12 cm (from tillering to flowering).

Rice is mostly cultivated as a monocrop in the same field for many years. Seedbeds are usually prepared by ploughing in autumn or spring at a depth of 20 cm, incorporating residues of the previous crop into the soil. Rice is mainly directly seeded, broadcasting seeds in flooded fields with fertilizer spreaders or by airplane (in Spain).

Fertilizer rates are typically:

- N: 80–120 kg/ha (50% in pre-planting and 50% in post-planting, using urea or other ammoniac fertilizers)
- P: 60–80 kg/ha (pre-seeding)
- K: 100–150 kg/ha (pre-seeding)

WEED SCENARIOS

Weeds are considered the worst noxious organisms affecting rice production in Europe. It is estimated that without weed control, at a yield level of 7 to 8 tonnes/ha, yield loss can be as high as 90 percent (Oerke *et al.*, 1994; Ferrero, Tabacchi and Vidotto, 2002). Weed problems are mainly related to competition with rice plants for light and nutrients, resulting in yield and quality reduction and an increase in the cost of harvesting and drying. Herbicides account for more than 80 percent of the total consumption of pesticides used in crop protection, with a total spending of about 110 million euros per year.

The important changes that occurred in most of the Western European countries during the 1960s in rice management – such as the change from transplanting to direct seeding, the expansion of mechanization and the introduction of chemical weed control – brought about a significant modification in the composition of the weed flora in rice fields.

The rice-field ecosystem is notably complex and the numerous weed species (both C_3 and C_4) present are characterized by particular morphophysiological traits. C_4 plants are mainly found in dry-seeded fields, while C_3 species tend to dominate in submerged rice crops (Bayer, 1991). Depending on the specific ecological conditions and anthropic pressure, some species may appear while others can disappear over time. The major weeds growing in European rice fields are aquatic (Batalla, 1989); they may be grouped on the basis of the practices adopted to control them (Ferrero, Tabacchi and Vidotto, 2002), as follows:

- *Echinochloa* species: *E. crus-galli, E. crus-pavonis, E. oryzoides, E. erecta* and *E. phyllopogon.* Major weeds in rice-cropping systems worldwide, in both water and dry-seeded rice (Holm *et al*., 1977; Ferrero *et al*., 2002), they have high variability in morphological and competition-related traits (e.g. plant size, tillering ability, seed dimensions and germination behaviour) (Barret and Wilson, 1983; Tabacchi *et al.*, 2006), which makes field identification of different species difficult and uncertain.
- *Heteranthera* species: *H. reniformis, H. rotundifolia* and *H. limosa*. Exotic plants first reported in Italy in 1962 (Pirola, 1968), in some areas they have become widespread in recent years and can compete severely with rice from its early stages (Ferrero, 1995).
- Alisma sedges and the sedges group (cyperaceae weeds) *Alisma plantago-aquatica, A. lanceolatum, Cyperus difformis, Bolboschoenus maritimus, Schoenoplectus mucronatus* and *Butomus umbellatus.* They are grouped together, as they are normally subject to common control programmes and are often sensitive to the same herbicides.
- Weeds in drill-seeded fields from two different floristic groups related to the different ecological conditions present on dry and flooded soil. Dry soil: *Echinochloa* spp, *Panicum dichotomiflorum, Bidens* spp, *Digitaria sanguinalis, Polygonum* spp, *Chenopodium album* and *Amaranthus retroflexus*. Flooded soil: weed species reported in fields flooded since rice planting. In these cultural conditions specific programmes of control are required for both groups of weeds.
- Weedy rice biotypes of cultivated rice (*Oryza sativa* L.). Diffused in much of the world, it is estimated that weedy rice infestations cover between 40 and 75 percent of European rice fields (Ferrero, 2003) and in Italy, France and Spain weedy rice infestations have been reported on 60 to 75 percent of the rice cultivated area.

At the seedling stage, weedy rice plants are difficult to distinguish from the crop, while after tillering the identification of the weed is possible thanks to many distinct morphological differences from the rice varieties: more numerous, longer and more slender tillers; leaves which are often hispid on both surfaces; tall plants; pigmentation of several plant parts; and easy seed dispersal after formation in the panicle (Kwon, Smith and Talbert, 1992). Weedy rice grains frequently have a red pigmented pericarp and the term "red rice" is commonly adopted in international literature to identify these spontaneous plants. This is not very appropriate, however, as red coat grains are also present in some cultivated varieties and absent in various weedy forms (FAO, 1999).

When the seeds break off and onto the soil prior to crop harvesting, the weeds disseminate and feed the soil seedbank (Ferrero and Vidotto, 1998). Following the shift from rice transplanting to direct seeding, red rice spread; the last 15 years have seen the problem worsen in Europe with the cultivation of weak, semi-dwarf *indica*-type rice varieties (Ferrero, 2003). The current spread is mainly related to the planting of commercial rice seeds containing grains of the weed.

WEED MANAGEMENT

All crop management practices may determine the competitive ability of rice and the weeds infesting rice fields. The shift in the early 1950s from transplanting to direct seeding and the abandoning of manual weeding resulted in greater infestations of weeds, including *Echinochloa* spp, *Alisma* spp, sedges and weedy rice plants. Weed management was complicated further following the introduction of short-stature rice varieties and the practice of shallow water in the fields during the early stages which created an ecological environment more favourable to their growth.

A sustainable programme of weed management must be based on a combination of cultural and chemical means: neither chemicals nor cultural practices alone can give satisfactory weed control (Bayer and Hill, 1993).

Cultural management

The main cultural operations that can have a significant direct or indirect impact on weed management are described below.

Soil tillage

Land preparation is an important component of rice weed control programmes: it helps the establishment and growth of rice while suppressing or delaying the development of weeds.

Tillage carried out in the autumn or winter increases soil aeration, favours straw decomposition and reduces algae infestations the following year. Established perennial weeds can then be partially devitalized if the soil dries out before field flooding for seeding the crop. Where perennial weeds are present, equipment fitted with rotary organs of tillage must not be used.

With soil tillage, fertilizers can be incorporated at a depth of 5 to 10 cm, reducing their availability to weeds which can germinate at the soil surface, and limiting nitrification and losses of nitrogen. With minimum tillage, weed seeds remain in the upper layers of the soil; they are spread uniformly and control is therefore more effective – both in pre-seeding (adopting the stale seed bed technique) and in early post-emergence.

Land levelling

Precision land levelling, obtained with laser-directed equipment, has made an important contribution to weedy rice management in European rice production. Level or regularly sloping fields enable appropriate water management, which limits weed growth and guarantees uniform emergence of weeds, which in turn makes herbicides more effective. With good soil levelling, the basin is larger and there are fewer ditches and levees from which weeds can spread into the fields.

Water management

Water management is central to weed control in water seeded rice. The water depth in rice fields has changed quite remarkably over the years, depending on the different growth features of the new varieties introduced in time (different vegetative vigour during the early stages, tall or short size of the plants, tillering degree etc.) and on the specific requirements of the herbicides applied.

In levelled fields, water is maintained at a depth of 5 to 7 cm until tillering and then at 12 to 15 cm until a few days before ripening. Rice fields are commonly drained 2 or 3 times during the crop cycle, in order to:

- hasten rooting of the rice seedlings;
- oxygenate the soil to avoid risks of unfavourable fermentation in the first few days after seed germination (7–15 days after seeding);
- destroy the algal scum;
- apply herbicides requiring drained soil conditions; or
- spread nitrogen fertilizers.

Most herbicides introduced into the market in recent years are characterized by foliar absorption and the plant surface must be well exposed to the herbicide spray. Dry conditions stimulate weed germination; therefore draining should be short to avoid the creation of different-aged weeds which are difficult to control with herbicides.

Rotation

Rotating rice with dry crops is an effective means of managing weeds that cannot be successfully controlled in rice. Where there are high infestations of weedy rice, the rotation of rice with non-flooded crops is the best solution to get a significant reduction of the seed-bank of this weed.

System of rice planting

On a small percentage of the cultivation area, rice is planted in dry soil and only flooded from the beginning of tillering until ripening; the rice fields are then infested by two different floristic groups related to the different ecological conditions of dry and flooded soil. While planting in dry soil reduces or delays the growth of those weed species requiring an aquatic environment (e.g. *Heteranthera* spp), it increases the development of non-aquatic weeds (e.g. *Panicum dichotomiflorum*, *Digitaria sanguinalis* and *Polygonum* spp). Weeds can be partially removed from dry fields with one or two passes of the tine harrow.

Varieties

The cultivation of *indica*-type and early-maturing varieties has significantly increased over recent years in European countries. Most *indica*-type varieties are short, have low growth and are only moderately competitive with weeds – all features which contribute to the spread of weedy rice infestations.

Early varieties usually have a cycle of 130–145 days (about 20–30 days shorter than regular varieties); they are popular because they escape the negative effects of the low temperatures in April and August when the delicate phases of emergence and flowering occur. High-yielding varieties planted in mid-May and which begin to flower before August are favoured. Where short-cycle varieties are selected, weedy rice control is carried out before rice planting.

Herbicide management

Herbicides are a fundamental element in sustainable weed management programmes. Numerous herbicides are available to control major rice weeds (Table 1) (Ferrero, Tabacchi and Vidotto, 2002). In recent years much effort has gone into developing herbicide programmes that maximize the use of commercial products while reducing the number of treatments.

Herbicide strategies are established mainly on the basis of the composition of the infestations. The key factors to be considered when deciding the weed control programme are the seeding conditions and the presence of weedy rice; the latter may influence the organization of the cultural practices or the choice of the herbicides.

Water seeding: infestations of* Echinochloa *spp,* Heteranthera *spp,* Alisma *spp, sedges and others

When weedy rice is absent and infestations are characterized by the presence of most common weeds (e.g. *Echinochloa* spp, *Heteranthera* spp and ciperaceae), two or three treatments are commonly required: one in pre-emergence (mainly against *Heteranthera* spp) and one or two 10–40 days after crop emergence.

TABLE 1
Rate and application timing of herbicides applied in Italy against main weeds of rice

Target weeds and active ingredients	Rates (*kg a.i./ha*)	Application timing
Echinochloa spp:		
Molinate	3.0–4.5	pre-seeding
	3.0–4.5	post-emergence
Thiobencarb	3.0–4.0	pre-seeding
	3.0–4.0	early post-emergence
Quinclorac	0.5–0.6	post-emergence
Propanil	3.5–4.0 + 3.5–4.0	late post-emergence
Bispyribac-sodium	0.02	early post-emergence
Profoxydim	0.1	early post-emergence
Azimsulfuron	0.02	early post-emergence
Cyhalofop-butyl	0.2–0.3	early post-emergence
Penoxsulam	0.04	early post-emergence
Imazamox	0.05	post-emergence (in combination with tolerant rice varieties)
Alismataceae and Cyperaceae:		
Bensulfuron-methyl	0.06	post-emergence
Cinosulfuron	0.06–0.08	post-emergence
Ethoxysulfuron	0.06	post-emergence
Bensulfuron-methyl + metsulfuron-methyl	0.05 + 0.002	late post-emergence
Metosulam	0.06–0.08	post-emergence
Azimsulfuron	0.02	post-emergence
MCPA	0.4–0.6	post-emergence
Triclopyr	0.3–0.4	late post-emergence
Bentazone	1.2–1.6	post-emergence
Penoxsulam	0.04	early post-emergence
Imazamox	0.05	post-emergence (in combination with tolerant rice varieties)
Heteranthera spp:		
Oxadiazon	0.2–0.4	pre-seeding
Pretilachlor	1.0–1.1	early post-emergence
Triclopyr	0.3–0.4	late post-emergence
Imazamox	0.05	post-emergence (in combination with tolerant rice varieties)
Weedy rice:		
Flufenacet	0.4	pre-seeding (30 days before seeding)
Pretilachlor	1.0	pre-seeding (30 days before seeding)
	1.0	post-emergence
Dalapon	12.0–15.0	pre-seeding (after stale seed bed)
Glufosinate-ammonium	1.0	pre-seeding (after stale seed bed)
Glyphosate	1.0–1.2	pre-seeding (after stale seed bed)
		crop post-emergence (wick bars)
Pretilachlor	1.2	pre-seeding (after stale seed bed)
Imazamox	0.05	post-emergence (in combination with tolerant rice varieties)

The first treatment is normally: oxadiazon (300–380 $g_{a.i.}$/ha) (to control *Heteranthera* species); combined with a graminicide (against *Echinochloa* plants, e.g. thiobencarb or molinate); and sometimes with an ALS inhibitor applied at one-half or one-third the normal rate (against sedges and other weeds). They are applied 3–4 days before planting and soil flooding, or 5–6 days before planting on flooded soil.

Second and sometimes third treatments are frequently necessary to control late emergences of *Echinochloa* spp, sedges, alismataceae and other species.

Water seeding: infestations with weedy rice, **Echinochloa** *spp,* **Heteranthera** *spp,* **Alisma** *spp, sedges and others*

Weed control programmes are principally aimed at weedy rice control and are carried out prior to seeding:

- with an antigerminative herbicide (e.g. flufenacet or pretilachlor) applied about 1 month before rice planting; or
- by mechanical means (harrows or a tractor fitted with cage wheels) or with systemic graminicides (e.g. dalapon, cycloxydim, clethodim or glyfosate) to destroy weedy rice seedlings grown after stale seedbed application (Table 1).

In both cases, a second treatment is usually required to control *Heteranthera* spp in rice pre-planting, and at least a third treatment with a mixture of specific herbicides, to control *Echinochloa* spp, sedges and other weeds, 25–40 days after rice planting.

When pre-planting treatments against weedy rice are not carried out or are unsatisfactory, there is often an intervention at rice flowering time. This can be manual when there are only a few weedy rice plants per ha, but with high infestations, the weed is devitalized by applying systemic herbicides (glyphosate) with wiping bars, provided that the weed plants are taller than those of the crop. The Clearfield® technology is particularly promising: it is based on the planting of a rice variety tolerant to imazamox, an imidazolinone herbicide with a wide spectrum of activity that also includes weedy rice plants.

Drill seeding: infestations with **Echinochloa** *spp,* **Panicum dichotomiflorum***,* **Digitaria** *spp,* **Polygonun** *spp,* **Alisma** *spp, sedges and others*

When rice is seeded in dry soil, two or three treatments are generally required (Table 1):

- First, in rice pre-emergence: pendimethalin (1 000–1 300 $g_{a.i.}$/ha) or clomazone (200–230 $g_{a.i.}$/ha) to control *Echinochloa* spp and other weed grasses; when *Heteranthera* spp is present, oxadiazon is usually added.
- Second, 10–30 days after rice emergence: propanil in combination with an ALS inhibitor to control sedges, *B. umbellatus*, *A. plantago-aquatica* and *Echinochloa* spp plants which escaped the pre-emergence treatment.
- Third, if necessary, just before flooding: against weeds which escaped previous treatments or emerged late, this intervention is sometimes performed after field flooding, applying the same products used in flooded rice fields.

Technological advances in the equipment mean that herbicides are sprayed with low water volume and at low pressure; this improves the efficiency of the products and limits the risk of environmental pollution. Furthermore, thanks to the increased width of the boom sprayers, fewer passes are made in the basins by tractors equipped with toothed wheels, thus diminishing both the cost of spraying and the frequency of late weed germinations which can occur along the wheel tracks.

When using herbicides, particular attention must be paid to water movement and depth in the rice field. Most ALS inhibitors require static water for a few days in order to avoid chemical removal and allow uniform soil absorption. Foliar herbicides (propanil, MCPA etc.) should be applied on drained fields for maximum exposure of the weed foliage to the spray. The improper use of herbicides can result in the appearance of resistant species, cause environmental pollution and risk disrupting the precarious balance of natural pest enemies.

The principal resistant weeds belong to *S. mucronatus*, *A. plantago-aquatica*, *C. difformis* and *Echinochloa* spp (Busi *et al.*, 2002). Studies of *C. difformis* and *S. mucronatus* have shown that there is a generalized cross resistance among several sulfonylureas (azimsulfuron, bensulfuron-methyl, cinosulfuron, imazamox and byspiribac-sodium) (Busi *et al.*, 2006). Some resistant populations are also insensitive to triazolopyrimidine herbicide (metosulam) at three times the recommended field dose (Sattin *et al*., 1999).

The main techniques currently adopted by European rice growers to tackle herbicide resistance are the rotation of herbicides and the application of mixtures of herbicides with different modes of action. For the successful control of ALS-resistant *Alisma* and sedges, farmers are increasingly using hormonic herbicides, such as MCPA which was widely used before the introduction of ALS inhibitors. Crop rotation – probably the best preventive and curative method for dealing with herbicide resistance – is unlikely to be adopted by farmers, for technical (soil suitability for other crops), economic and organizational reasons.

Environmental contamination from herbicide use is an important issue requiring attention (Ferrero *et al*., 2001), with particular regard to the choice of active ingredients having low solubility in water, low volatilization and low persistence.

CONCLUSIONS

Weed management is a major concern for rice growers, as unsuccessful weed control can result in a severe reduction in yield and quality.

The dramatic technological advances of recent decades have influenced rice management: the development of mechanization; the introduction and diffusion of chemical weed control; the change from transplanting to direct seeding; and the introduction of late, dwarf and less competitive rice varieties. All these changes determined important modifications in the composition of the weed flora in rice fields. Weeds such as *Echinochloa* spp, *Alisma* spp, cyperaceae species and weedy rice – previously well controlled by hand-picking or limited in their growth by transplanting – became increasingly competitive. The introduction of rice seed from other countries favoured the diffusion of exotic weeds such as *Heteranthera* spp. The numerous herbicides now available, and which are suited to every floristic situation, help limit yield losses but often do not prevent weed spread and pressure. The improper use of herbicides may lead to the development of resistance in some weeds or to environmental pollution. The main issues in rice weed management can be addressed by integrated strategies based on an appropriate combination of herbicides with good agronomic practices.

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Lutte anti-adventices dans les champs de riz d'Europe

Les adventices sont les organismes les plus nuisibles à la culture du riz en Europe. Les principales infestations d'adventices peuvent actuellement être regroupées de la façon suivante:

1. Espèces du genre *Echinochloa*
2. Espèces du genre *Heteranthera*
3. Espèces du genre *Alisma* et adventices de la famille des Cypéracées (laîches)
4. Mauvaises herbes des champs ensemencés en ligne
5. Biotypes de riz propices à l'infestation par les adventices

Les principales pratiques culturales actuellement en usage dans la culture du riz – labour et préparation du sol, nivellement du sol, gestion de l'eau, rotations, semis, variété choisie – peuvent avoir un impact significatif, direct ou non, sur la lutte anti-adventices. Plus de 80 pour cent des produits phytosanitaires utilisés pour la culture du riz sont des herbicides. Les principaux herbicides utilisés visent *Echinochloa* spp. (Molinate, Propanil, Thiocarbazil, Dimepiperate, Quinclorac, Cyalofop-butyl, Penoxulam, Azimsulfuron et Bispyribac-sodium), *Heteranthera* spp. (Oxadiazon) et les espèces de la famille des Alismatacées et des Cypéracées (Bensulfuron-methyl, Cinosulfuron, Ethoxysulfuron, Azimsulfuron, Bispyribac-sodium, Metosulam, MCPA et Bentazone). L'utilisation inconsidérée des herbicides aboutit occasionnellement à une pollution de l'eau ou du sol, ou à la sélection d'adventices résistantes. À la suite de l'application d'herbicides inhibiteurs d'ALS, il a été rapporté des pertes de maîtrise de la lutte contre *Alisma plantago-aquatica*, *Schoenoplectus mucronatus* et *Cyperus difformis,* ainsi que pour *Echinochloa* spp. à la suite d'application de Propanil.

Les approches les plus couronnées de succès en matière de lutte anti-adventices dans les champs de riz sont actuellement celles qui reposent sur des pratiques de conduite intégrée des cultures, associant des herbicides spécifiques et des pratiques agronomiques appropriées.

El control de malezas en los arrozales de Europa

Las malezas son los organismos nocivos que más daños causan a los arrozales europeos. En la actualidad, las malezas principales pueden agruparse como sigue:

1. Especie *Echinochloa*
2. Especie *Heteranthera*
3. Especie *Alisma* y malezas ciperáceas
4. Malezas de los campos sembrados con sembradoras en línea
5. Biotipos de arroz maleza

Las principales operaciones aplicadas actualmente en el cultivo de arroz –labranza y preparación de la tierra, nivelación del terreno, regulación de aguas, rotación, plantación, elección de la variedad– pueden tener un efecto directo o indirecto importante en el control de malezas. Los herbicidas representan más del 80 % del consumo total de plaguicidas destinado a la protección de los cultivos. Los principales herbicidas aplicados en el control de malezas se emplean en la lucha contra *Echinochloa* spp. (molinate, propanil, tiocarbacilo, dimepiperato, quinclorac, cihalofop-butilo, penoxulam, azimsulfurona y bispiribaco de sodio), *Heteranthera* spp. (oxadiazona) y las especies *Alismataceae* y *Cyperaceae* (bensulfuron-metilo, cinosulfuron, etoxisulfuron, azimsulfurona, bispiribaco de sodio, metosulam, MCPA y bentazona). El uso impropio de herbicidas provoca ocasionalmente la contaminación del suelo y el agua, o el desarrollo de resistencia en las malezas. Existen informes de falta de control de *Alisma plantago-aquatica*, *Schoenoplectus mucronatus* y *Cyperus difformis* tras la aplicación de herbicidas inhibidores de la enzima ALS, y de *Echinochloa* spp. después de la aplicación de propanilo.

Actualmente, los métodos más eficaces para el control de malezas de los arrozales se basan en la aplicación de prácticas integradas de gestión de cultivos que emplean una combinación de herbicidas con prácticas agronómicas apropiadas.

Rice genetic potential and its application in rice breeding for stress tolerance

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INTRODUCTION

Using the vast genetic potential of the rice collection and modern methods of creation and evaluation of the breeding material, the All-Russia Rice Research Institute (ARRRI) has released a number of varieties resistant to environmental stress factors, well adapted to local conditions and widely used. ARRRI also provides a valuable source of basic material for breeding new generation rice varieties. An analysis of rice production in the Russian Federation reveals the negative effect of the permanent increase in fuel prices: the self-cost of the grain rises and its competitive ability declines. The solution is seen in the development and introduction of energy-saving, ecologically safe rice-growing and harvesting methods, as well as in the breeding of new varieties. Varieties need to combine low energy requirements with adequate productivity, resistance to diseases and environment stress factors, and growth ability without the application of herbicides. The last 20 years of research at ARRRI have been dedicated to the release of such rice varieties.

SAMPLE ASSESSMENT: THE FOUNDATION OF RICE BREEDING

The success of breeding activities largely depends on the availability of diverse initial material and the bank of crop genetic resources. Principal activities include the collection, safe-keeping, study, description and provision to rice breeders of samples. Rice collection in the Russian Federation was initiated in the 1920s by the specialists of the All-Union Institute of Plant Industry (VIR) under the guidance and with the direct participation of Mr N.I. Vavilov. The collection currently contains over 5 000 samples belonging to varieties and types that reach maturity under the climatic conditions in the Russian Federation. Special nomenclature of the *Oryza* L. genus has been established for rice evaluation using uniform assessment methods. The best rice samples in the world are included in the ARRRI working collection comprising over 3 000 viable samples of various pedigrees, including: mutants and polyploids; varieties that have been rejected or that did not pass the tests; selections from hybrid populations of senior generations; the best varieties in the world collection; and varieties commercially grown in Russia.

ARRRI and breeding centres in other rice-growing countries exchange material so as to have access to the latest achievements in world rice breeding for the creation of new varieties. Quarantine and introductory nurseries prevent the introduction of quarantine pests and diseases with rice seeds received from other countries.

The majority of varieties coming to Russia from other countries are late-maturing and – being as a rule native of the tropical zone – they are photosensitive and react to a 16-hour photoperiod (under conditions in Krasnodar) with an increased vegetation period of 150–160 days or more. The majority of samples do not reach heading and many of them are used only for hybridization under conditions of climatic chamber.

Foreign samples are often used as sources of traits such as short stem, long grain, high milling qualities, and resistance to pests, diseases and environmental stress factors; in return, ARRRI sends collection samples in response to the requests of foreign colleagues. Rice breeders in other countries evaluate the ARRRI samples and report back on the behaviour of the material under local conditions, providing interesting data, in particular with regard to the degree of resistance to pests and diseases under other ecological conditions.

EVALUATION OF COLLECTION MATERIAL

Every sample in the ARRRI working collection undergoes complex evaluation of 40 traits to identify potential donors of economically valuable features. The samples are studied under field and vegetative conditions and in laboratory tests, with the participation of numerous specialists: plant breeders, specialists in genetics, plant physiology, biochemistry and phytopathology from ARRRI and other research institutes.

In standard field experiments, the samples are evaluated and described according to their morphological traits, and their resistance to logging and shedding, and to pests and diseases is defined. In special experiments under provocation settings, the resistance to salinity, low temperatures, blast, aphids and rice leaf nematode is evaluated; the reaction to high nitrogen rates is also determined. Under laboratory conditions, the rice grain is assessed for its milling qualities: total milled rice and white rice, vitreousity, filminess, fracturing, grain size and form, and weight of 1 000 grains. The protein and amylose content is also defined.

Sources of early maturity, high-yielding ability, high grain quality, increased protein and amylose content, salt and cold tolerance, and resistance to pests and diseases are selected. An important feature is high yield, which is obtained by individual productivity of plants under optimal plant density. The working collection is constantly replenished with high production samples created in the course of breeding research. As productivity depends on the duration of the vegetation period, most sources of high productivity are medium- and late-maturing. Russian rice growing is one of the northernmost in the world; therefore special attention is paid to breeding rice with a short vegetation period (Table 1). ARRRI breeders use early-maturing (up to 100 days of vegetation) and fast-maturing (100–110 days) rice samples to obtain early-maturing primary material. The collection includes over 250 samples.

Rice breeding for cold tolerance is based on valuable samples which combine tolerance to low temperatures with other economically valuable traits. Each year ARRRI plant physiologists evaluate 100–150 collection samples for cold tolerance and the best are recommended for hybridization. The samples obtained though breeding for cold tolerance are added to the germplasm bank (Table 2).

Large areas of rice systems are subject to increased salinity; breeding programmes for salt tolerance were therefore initiated. To define the sources of salt tolerance, as many as 400 samples from working and world collections are assessed each year. The best samples – combining high salt tolerance with other positive traits – are recommended for further breeding programmes (Table 3).

Under Russian Federation conditions the most noxious disease in rice fields is blast, caused by fungus *Pyricularia oryzae* Cav. All collection samples are therefore evaluated for resistance to this disease and the best are used in hybridization (Table 4).

In addition to high productivity and resistance to diseases and environmental stress factors, varieties should have vitreous grain and resistance to crushing – able to give maximum total milled rice and more economically efficient. Russian rice breeders aim to release high-quality varieties meeting modern market demand: Table 5 lists samples combining high quality of milled rice with maximum number of economically valuable traits.

Protein content is an important indicator of rice alimentary quality. Protein is 98 percent assimilated by the human organism, and low protein rice varieties contain 7.33 percent protein (dry matter) while high-quality varieties up to 11.9 percent. ARRRI biochemists have selected samples combining increased protein content with maximum content of amylose (Table 6).

Under Russian Federation conditions, the selected collection samples accumulate more protein and amylose than Krasnodarsky 424; they provide basic material for these traits and are recommended for breeding. The data obtained for each sample are registered in a special logbook and on catalogue cards and any hybridization

TABLE 1
Collection samples as sources of early maturity

ARRRI catalogue number	No. days from flooding to flowering	Plant height (*cm*)	Resistance to lodging (*points*)
03455	59	78.8	9
03456	59	69.8	9
03527	59	76.0	5
03530	66	82.1	7
03534	62	79.9	9
03537	60	74.8	5
03540	50	84.6	9
01317 – standard	67	82.4	7

TABLE 2
Collection samples as sources of cold tolerance

ARRRI catalogue number	No. days from flooding to flowering	Plant height (*cm*)	Cold tolerance (*points*)
0856	77	101.2	9
02990	62	86.1	9
03054	63	90.7	9
03305	77	94.8	9
03333	74	115.2	9
03339	68	85.6	9
03584	72	86.4	9
01310 – standard	75	101.0	9

TABLE 3
Collection samples as sources of salt tolerance

ARRRI catalogue number	No. days from flooding to flowering	Plant height (*cm*)	Salt tolerance (*points*)
0812	73	73.5	7
02231	77	82.7	7
02432	65	69.0	7
02625	73	69.9	7
02712	63	70.7	7
03064	61	91.5	7
03225	73	97.6	7
01318 – standard	82	85.0	7

includes data analysis for parent selection. ARRRI created the Rice Genetic Resources Database for: storing and processing of information on rice collection; automatic searches for sources of required traits; and the development of breeding programmes. Information about the collection is obtained rapidly and sample use is improved, in particular when there is a rare combination of individual traits.

METHODS OF CREATION OF BASIC MATERIAL FOR BREEDING NEW RICE VARIETIES

The principal method used at ARRRI for breeding basic material is intraspecific hybridization. Mutagenesis and biotechnological methods are widely adopted for production of new forms. Modern methods of hybridization include castration and flower pollination. The most efficient – while simple – method is pneumatic castration, for which a special device has been developed: the panicles are pollinated on the castration day and the parents are grown in climatic chambers under optimal thermal and photoperiod conditions. Hybridization programmes are carried out all year round.

The application of pneumatic castration and pollination are responsible for the considerable increase in hybrid grains: every year the ARRRI hybridization centre receives for 120–130 combinations (i.e. 40 000–50 000 flowers) as many as 20 000 hybrid grains. The average grain setting is 50–60 percent and for some combinations it reaches 90 percent; there is a high output of true first generation hybrids from 93.1 to 98.0 percent.

TABLE 4
Collection samples as sources of blast resistance

ARRRI catalogue number	No. days from flooding to flowering	Plant height (*cm*)	Plant susceptibility (*points*)	
			Leaf	Panicle
010	84	60.0	0	0
020	83	100.0	0	0
01089	94	89.5	0	0
01179	93	94.1	0	0
01970	88	86.0	0	0
02056	87	99.2	0	0
02344	86	86.8	0	0
02384 – standard	119	118.0	5	7

TABLE 5
Collection samples used as sources of high grain quality

ARRRI catalogue number	No. days from flooding to flowering	Plant height (*cm*)	Total (*%*)	
			Milled rice	Head rice
0252	111	91	72.6	99.7
01458	112	107	72.0	95.6
01746	107	50	71.8	98.5
02313	106	113	72.3	91.6
02898	111	107	71.1	98.2
12901	118	83	71.6	98.4
03060	114	124	72.5	92.5
03198	102	101	72.5	97.8
02384 – standard	119	118	71.6	91.7

TABLE 6
Rice samples with high content of protein and amylose

ARRRI catalogue number	Sample designation	Content (%)	
		Protein	Amylose
01202	Mutant 68	10.5	19.0
01730	Mutant 4207	12.0	18.8
01841	VNIIR 6955	11.0	19.6
02231	VNIIR 9199	11.0	18.4
02687	Line 84-1-25-2-1	11.3	19.0
03463	VNIIR 751	9.5	19.2
03486	DZ-192	10.7	17.8
03636	KP-108-87	10.7	18.8
02384 – standard	Krasnodarsky 424	9.5	15.4

F_1 hybrids are grown in vegetation vessels: in winter in climatic chambers and in summer on vegetation plots. To overcome the problem of newly harvested seed germinating, the dormancy period is interrupted: F_1 hybrid grains are warmed in hot water (70 °C) for 7–10 minutes, then thermostat-controlled at 40 °C for 24 hours. Further germination then takes place at 28–30 °C (thermostat-controlled), reaching 95–98 percent. Hybrids of second and subsequent generations are evaluated and multiplied under field conditions. Rice breeders select elite plants with pre-planned parameters for the development of a breeding nursery.

Over the ensuing years the material obtained is studied according to generally accepted breeding methods. The evaluation process is performed by various scientists and specialists in phytopathology, entomology, plant physiology, biochemistry and rice grain milling quality. Before varieties are handed over for state evaluation, farming methods are developed and primary seed production is started. Every year ARRRI specialists issue two or three different varieties for state evaluation, including ones tolerant to environmental stress factors. The state register includes varieties with various characteristics: Sprint, Slavyanets and Leader (adapted for herbicide-free management systems); Kurchanka (salt tolerant); Viola (glutinose); and Snezhinka (long-grain) – see Table 7. While they share high grain milling quality and tolerance to stress factors, they have very different morphological traits and biological properties, outlined below:

- Sprint (fast-maturing) and Leader (medium-late-maturing) are characterized by low requirements in terms of growing conditions and their fast growth during emergence when the shoots easily overcome a water layer of 20 cm; they are therefore recommended for cultivation without application of herbicides. Resistance to blast means that fungicide treatments are not necessary.
- Slavyanets (medium-maturing) is increasingly widely grown and belongs to universal varieties; it can be grown using any farming methods accepted in the farm.
- Kurchanka (salt-tolerant) is suitable for cultivation in rice fields with increased soil salinity, where it has achieved yields 500–600 kg/ha higher than other varieties. This variety is salt tolerant at both emergence and flowering, when other varieties are especially susceptible to salinity.
- Snezhinka (long-grain, *indica*) produces high-quality milled rice. Following state tests and production verification, the variety was included in the state register and admitted for commercial production. It requires no special methods during growth; it possesses effective blast resistance genes and therefore needs no chemical treatments. Processing the long grains remains a problem, however: the equipment in factories is adapted to milling short-grain varieties and so efforts are still required in this area.
- Viola (glutinous) was state commissioned for use in baby and diet food. The variety has been tested and patented in the Russian Federation.

TABLE 7
Performance of rice varieties resistant to environment stress factors

Variety	Vegetation period (*days*)	Plant height (*cm*)	Emerging rice growth rate (*points*)	Grain type (*l/b*)	Total milled rice (*%*)	Blast resistance
Sprint	87–90	90–95	9	1.8	72	Resistant
Slavyanets	112–117	85–95	8	1.7	71	Resistant
Leader	120–122	90–95	9	1.7	71	Resistant
Kurchanka	120–122	80–85	8	2.4	71	Average resistance
Snezhinka	120–122	90–95	7	4.0	68	Resistant
Viola	112–116	75–80	9	1.7	68	Resistant

CONCLUSION

Using the vast genetic potential of the rice collection and applying modern methods of creation and evaluation of the breeding material, ARRRI has released varieties with resistance to environmental stress factors, well adapted to local conditions and widely used. In addition to these varieties, there are valuable sources of basic material for breeding rice varieties of new generations.

Le potentiel génétique du riz et ses applications à la sélection de variétés résistantes au stress

En raison de la hausse continuelle des prix de l'énergie et des coûts internes de la production céréalière, il est nécessaire de mettre au point des pratiques culturales économes en énergie et non nocives pour l'environnement, ainsi que de sélectionner des variétés nouvelles. La réussite des activités de sélection dépend en grande partie de la disponibilité de matériel génétique de base diversifié et d'une banque de ressources génétiques agricoles confirmée. Les meilleures obtentions de riz à l'échelle mondiale sont contenues dans la collection de travail de l'Institut de Recherche rizicole de toutes les Russies (ARRRI). Il est donc possible de disposer de sources de caractéristiques telles que maturité précoce, capacité de haut rendement, bonne qualité du grain, teneur en protéines et en amylose améliorées, tolérance au froid et à la salinité, et résistance aux parasites et aux maladies. La maladie la plus destructrice présente dans les champs de riz de la Fédération de Russie est la nielle du riz, causée par la moisissure *Pyricularia oryzae* Cav. La principale méthode de sélection à partir de nouveaux matériels génétiques de base utilisée à l'ARRRI est l'hybridation intraspécifique. La mutagenèse et d'autres méthodes de biotechnologie sont couramment utilisées pour produire des variétés nouvelles. Les méthodes modernes d'hybridation comprennent la castration et la pollinisation des fleurs. Le document présente les résultats obtenus par l'ARRRI dans l'utilisation de ressources génétiques rizicoles pour la sélection de variétés améliorées au cours des 20 dernières années.

El potencial genético del arroz y su aplicación en el mejoramiento para obtener tolerancia al estrés

A causa del constante aumento de los precios del combustible, y el costo unitario creciente de la producción de cereales, se hace necesario desarrollar métodos de cultivo y recolección del arroz que permitan ahorrar energía y sean seguros desde el punto de vista ecológico. Es preciso, además, seleccionar nuevas variedades. El éxito de las actividades de mejoramiento depende en gran medida de que se pueda contar con material inicial diverso y con un banco establecido de recursos fitogenéticos. Las mejores muestras de arroz disponibles en todo el mundo se encuentran en la colección de trabajo del Instituto ruso de investigación sobre el arroz (ARRRI). Gracias a ello es posible seleccionar fuentes de maduración rápida, con capacidad de proporcionar altos rendimientos, granos de alta calidad, un contenido más elevado de proteínas y amilasa, más sal y tolerancia al frío, y que ofrezcan resistencia a las plagas y enfermedades. La enfermedad más nociva que ataca los arrozales de la Federación de Rusia es el añublo del arroz, provocado por el hongo *Pyricularia oryzae* Cav. El principal método de mejoramiento que se emplea para el nuevo material básico del ARRRI es la hibridación intraespecífica. Existe un amplio uso de la mutagénesis y los métodos biotecnológicos para producir nuevas formas. Los métodos modernos de hibridación incluyen la castración y la polinización de las flores. Este informe presenta los resultados de la aplicación de los recursos genéticos del arroz en la actividad de mejoramiento destinada a obtener variedades mejoradas del cereal que se ha llevado a cabo en el ARRRI durante los últimos 20 años.