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Preface

This publication deals with the direct application of phosphate rock (PR) sources to agriculture. Phosphorus (P) is an essential plant nutrient and its deficiency restricts crop yields severely. Tropical and subtropical soils are predominantly acidic, and often extremely P deficient with high P-sorption (fixation) capacities. Therefore, substantial P inputs are required for optimum plant growth and adequate food and fibre production.

Manufactured water-soluble P fertilizers such as superphosphates are commonly recommended to correct P deficiencies, but most developing countries import these fertilizers, which are often in limited supply and represent a major outlay for resource-poor farmers. In addition, intensification of agricultural production in these countries necessitates the addition of P not only to increase crop production but also to improve soil P status in order to avoid further soil degradation. Hence, it is imperative to explore alternative P sources. Under certain soil and climate conditions, the direct application of PR, especially where available locally, has proved to be an agronomically and economically sound alternative to the more expensive superphosphates. PR deposits occur worldwide, but few are mined (for use mainly as raw materials to manufacture water-soluble P fertilizers).

The Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture initiated a Coordinated Research Project called "The use of nuclear and related techniques for evaluating the agronomic effectiveness of phosphatic fertilizers, in particular rock phosphates". This was implemented by institutes of developing and industrialized countries from 1993 to 1998. The results obtained yielded new information on: chemistry of soil P; tests for available soil P; phosphate nutrition of crops; agronomic effectiveness of PR products; and P fertilizer recommendations with particular emphasis on PR use.

Within the framework of the integrated plant nutrition systems promoted by the Land and Water Development Division (AGL), FAO, and the national action plans for soil productivity improvement under the Soil Fertility Initiative for sub-Saharan countries, PRs are considered as potentially important locally available P sources. AGL has instituted several studies on the agro-economic assessment of PRs for direct application in selected countries. Results of practical utility and policy guidelines can be drawn from these studies.

Several organizations have conducted extensive research on the utilization of indigenous PR deposits in tropical soils in Latin America, Africa, Asia and elsewhere. In the past decade, considerable progress has been made in the utilization of PR sources for direct application in agricultural cropping systems worldwide. A wealth of information is now available but scattered in several publications.

Recognizing the need for the wider dissemination of the available information, the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture together with the AGL convened a Consultants' Meeting in Vienna in November 2001 in order to review advances in this field of research and development, and to elaborate a proposal for the production of this technical bulletin. Mr F. Zapata (IAEA, Vienna) and Mr R.N. Roy (FAO, Rome) implemented this task. Specialists in the sector were invited to contribute to the chapters of the publication.

This publication presents the results of studies on the utilization of PR products for direct application in agriculture under a wide range of agro-ecological conditions with a view to fostering sustainable agricultural intensification in developing countries of the tropics and subtropics. The subject matter is covered in 12 chapters, contributed by a team of scientists involved in PR research and working in a wide range of disciplines including geology, chemistry, soil science, agronomy and economics, etc. In addition, the publication includes a comprehensive bibliography.

Chapter 1 provides background information on: P as an essential plant nutrient; soil P status; the need for the application of P fertilizers; and the potential for using PRs in the context of food security, soil degradation and environmental protection. It describes generalities on the nature and variability of PR sources worldwide and provides an overview of past and current work and of the prospects for the utilization of PR products for direct application in agriculture. Chapter 2 deals with the type and distribution of PR geological deposits worldwide. It provides information on: inventory of reserves; PR production; and PR consumption for direct application. Chapter 3 describes the characterization of PR products in view of their wide variability for utilization as a raw material for the manufacture of P fertilizers and for direct application in agriculture. This includes information on: mineralogical composition of the phosphate-bearing minerals (main and accessory), in particular, the crystallographic features and empirical formulae of the apatite minerals; chemical composition (main chemical elements including micro-elements, heavy metals and radionuclides); solubility indices as indicators of reactivity; and physical properties (particle-size distribution, specific surface area, and hardness). Chapter 4 examines the approaches and methodologies for evaluating PR for direct application, such as solubility tests, soil incubation, greenhouse tests and field evaluation. For each approach, the chapter provides an overview of the objectives, methods and measurements with examples. It also provides a brief description of the advantages and limitations of the methods, and special considerations for interpreting results. Chapter 5 provides an up-to-date review of the main factors that affect the agronomic effectiveness of PR products. Selected case studies provide region-level examples of the influence of these factors and their interactions, and economic guidelines. Chapter 6 describes soil P testing methods for providing recommendations for PR application. It discusses principles and considerations for interpreting the results of ‘available P’. Chapter 7 focuses on the need for and the development and testing of a decision-support system to predict the agronomic effectiveness of PR for direct application, together with the use of P modelling. Chapter 8 examines current knowledge, and gaps therein, on the effects of other elements present in PR products. It covers beneficial and hazardous elements, such as calcium and magnesium, micronutrients, heavy metals and radionuclides. Chapter 9 describes approaches and technologies for improving the agronomic effectiveness of indigenous PRs. Chapter 10 examines the economic criteria to be considered in the production, marketing and distribution of PRs. It discusses macroeconomic and microeconomic issues, and includes case studies on the exploitation of PR deposits. Chapter 11 provides an overview of current regulations on PR for direct application. Legislative guidelines are proposed for consideration. Chapter 12 is an epilogue containing the main conclusions and issues for further consideration.

The aim of this publication is to provide the most up-to-date information on the direct application of PR in agriculture. It endeavours to do this in a technically focused document that leads on to practical guidelines to assist middle-level decision-makers, the scientific community, higher-level extension workers, non-governmental organizations and other stakeholders involved in agricultural development. The ultimate goal is to maximize technology dissemination in a targeted way, particularly for policy-makers at all levels who may require information on the adoption of PRs as a capital investment to trigger sustainable agricultural intensification in the acidic soils of the tropics and subtropics.

Contributing authors

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Chapter 11 Legislation and quality control of phosphate rocks for direct application, by S.H. Chien (IFDC, the United States of America)

Chapter 12 Epilogue, by R.N. Roy (FAO, Italy) and F. Zapata (FAO/IAEA, Austria)

List of abbreviations and acronyms

^{32}P	Phosphorus-32 (radioisotope)
AEI	Agronomic economic efficiency
AGL	Land and Water Development Division, Agriculture Department, FAO
Al	Aluminium
As	Arsenic
ASI	Absolute solubility index
BNF	Biological nitrogen fixation
BPL	Bone phosphate of lime
BRGM	Bureau of Geological and Mining Research (France)
C	Carbon
Ca	Calcium
CA	Citric acid
CCE	Calcium carbonate equivalent
Cd	Cadmium
CGIAR	Consultative Group on International Agricultural Research
CIRAD	Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement
Cl	Chlorine
CMDT	Malian Company for the Development of Textiles
CO_2	Carbon dioxide
C_p	P ion concentration in soil solution
Cr	Chromium
CR	Equilibrium P concentration sustained by a PR
CRP	Coordinated research project
Cu	Copper
DAP	Di-ammonium phosphate
DAPR	Direct application phosphate rock
Dm	Mean diffusion
DSS	Decision-support system
DSSAT	Decision Support System for Agrotechnology Transfer
E value	Exchangeable P
E_1	Isotopically exchangeable P at 1 minute
EC	European Community
EDS	Energy dispersive X-ray analysis
F	Fluorine

FA	Formic acid
FAO/IAEA	Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture
Fe	Iron
FSU	Former Soviet Union
H	Hydrogen
Hg	Mercury
IAEA	International Atomic Energy Agency
ICRAF	International Centre for Research in Agroforestry
IEK	Isotopic exchange kinetic
IFDC	International Centre for Soil Fertility and Agricultural Development, formerly International Fertilizer Development Center
IMPHOS	Institut Mondial du Phosphate
K	Potassium
L	Labile
LDCs	Least developing countries
LOI	Loss on ignition
MAP	Mono-ammonium phosphate
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
NAC	Neutral ammonium citrate
NGO	Non-governmental organization
NORAGRIC	Centre for Environment and International Development, Agricultural University of Norway
NPK	Compound nitrogen, phosphorus and potassium containing fertilizers
NPV	Net present value
O	Oxygen
P	Phosphorus (element)
P fertilizer	Phosphatic fertilizer
P_2O_5	Phosphorus pentoxide (phosphate)
PAPR	Partially acidulated phosphate rock
Pb	Lead
P_i	Iron-oxide-impregnated paper
PPCL	Pyrites, Phosphates and Chemicals Ltd. (India)
PR	Phosphate rock
PR/S	Phosphate rock elemental sulphur assemblage
PR-DSS	Phosphate rock decision-support system
PRs	Phosphate rocks, PR materials, PR products
PSM	Phosphate solubilizing micro-organisms

RAE	Relative agronomic effectiveness
RELARF	Red Latinoamericana de Roca Fosforica
RPR	Reactive phosphate rock
RR	Relative response
Se	Selenium
SEM	Scanning electron microscopy
SFET	Soil fertility enhancing technology
SFI	Soil Fertility Initiative
Si	Silicon
SSP	Single superphosphate
STPP	Sodium tri-polyphosphate
SV	Substitution value
SV50	Substitution values of TSP (50% maximum yield) for North Carolina PR
TPR	Tilemsi phosphate rock
TSP	Triple superphosphate
U	Uranium
USGS	United States Geological Survey
V	Vanadium
VAM	Vesicular-arbuscular mycorrhizae
WSP	Water-soluble phosphate
XRD	X-ray diffraction
Zn	Zinc

Executive summary

In order to ensure food security in developing countries, there is a need for the sustainable intensification of agricultural production systems towards supporting productivity gains and income generation. In this context, novel, soil-specific technologies will have to be developed, pilot tested and transferred to farmers in a relatively short time. Phosphorus (P) is an essential nutrient element for plants and animals. The appropriate and sound utilization of phosphate rocks (PRs) as P sources can contribute to sustainable agricultural intensification, particularly in developing countries endowed with PR resources.

PR is a general term used to describe phosphate-bearing minerals. PR is a finite, non-renewable natural resource. Geological deposits of different origin are found throughout the world. Currently, few PR deposits are mined, and about 90 percent of world PR production is utilized by the fertilizer industry to manufacture P fertilizers, with the remainder being used to manufacture of animal feeds, detergents and chemicals. However, many PR deposits located in the tropics and subtropics have not been developed. One reason is that the characteristics of these PRs, though suitable for direct application, do not meet the quality standards required for producing water-soluble P (WSP) fertilizers using conventional industrial processing technology. Another reason is that the deposits are too small to warrant the investment needed for mining and processing. On a worldwide basis, there is ample supply of high-quality PRs for chemical processing and direct application for the foreseeable future.

PR is the primary raw material for producing P fertilizers. The phosphate compound in PRs is some form of the mineral apatite. Depending on the origin of the PR deposit and its geological history, the apatites may have widely differing chemical and crystallographic characteristics and physical properties. Distinctive suites of accessory minerals are also associated with PRs of various origins and geological histories. It is imperative to establish simple procedures for the standard characterization of PR sources, define quality standards for their direct application and categorize them. Well-known PR sources may be adopted as reference standards for comparison purposes.

The mineralogical, chemical and textural characteristics of phosphate ores and concentrates determine: (i) their suitability for various types of beneficiation processes to upgrade the ores and remove impurities; (ii) their adaptability for chemical processing by various routes; and (iii) their suitability for use as direct application phosphate rock (DAPR). The most important factors in the assessment for direct application are: grade, suitability for beneficiation, and the reactivity of the apatite. A comprehensive characterization matrix based on the integration of all the data obtained by various analytical methods brings out the beneficiation potential and probable best uses for a PR in fertilizer processing and as a direct application fertilizer.

There are various methods for evaluating PRs for direct application. The first approach uses empirical solubility tests with the PR being dissolved in chemical extracting solutions. The most common solutions are neutral ammonium citrate, 2-percent citric acid, and 2-percent formic acid, with the last option being preferred. The particle size of the PR and associated minerals in the PR can influence the result of the solubility test. Radioisotopic techniques can be used but they require skilled staff and special laboratory facilities. Soil incubation studies to evaluate

PRs are relatively simple. However, closed incubation studies have limitations as reaction products are not removed and the results would have limited utility unless used as short-term observations. Greenhouse experiments are valuable in that they enable the performance of the PR to be evaluated under controlled conditions. However, the final evaluation of the agronomic effectiveness of PR sources in a network of field experiments conducted over a number of growing seasons at representative sites in the agro-ecological regions of potential interest is essential. A series of recommendations for undertaking such evaluation have been developed. Such evaluation is also required for the assessment of the economic potential of PR deposits for domestic consumption.

Factors that influence the agronomic effectiveness of PRs are: the reactivity of the PR, soil properties, climate conditions, crop species and management practices. High carbonate substitution for phosphate in the apatite crystal structure, low content of calcium carbonate as accessory mineral and fine particle size (less than 0.15 mm) enhance the reactivity of PRs and their agronomic effectiveness. Rapid chemical tests are available to measure the reactivity of PRs. Increasing soil acidity, high cation exchange capacity, low levels of calcium (Ca) and phosphate in solution and high organic matter content favour PR dissolution. High phosphate retention capacity of soils may facilitate dissolution of PR but the availability of dissolved P will depend on the concentration of phosphate maintained in solution. Soils of medium phosphate status are considered to be more suitable for PR application than severely phosphate-deficient soils. Increasing rainfall invariably results in improved agronomic effectiveness of PRs. High agronomic effectiveness of PRs may be realized with perennial and plantation crops and also with legumes. To achieve maximum agronomic effectiveness, the PRs should be incorporated into the soil. While only a maintenance rate of P application need be applied as PR where the soil phosphate status is medium or above, very high rates of application are required for severely phosphate-deficient soils. Application time can be nearer to planting in very acid soils ($pH < 5.5$) and 4–8 weeks before planting in less acid soils.

The potential for using local PRs for direct application varies for each country as the complexity of the interactions occurring between specific local factors is evident in the tropical and subtropical world. Countries with substantial reactive PR reserves, such as Mali, Madagascar and Indonesia, offer considerable scope for the direct application of PRs. In countries endowed with less reactive PR reserves, such as Venezuela and Brazil, it is feasible to modify the PRs in order to improve their performance. In some cases, the economic advantage to the farmer can be considerable, as evidenced in the example on Venezuela. The Indian case study reveals import replacement as the major economic benefit resulting from the use of local Mussoorie PR. The New Zealand case study illustrates a success story on the use of reactive phosphate rocks (RPRs) for pastoral agriculture in Oceania.

Conventional soil tests for available P estimation are used for formulating fertilizer recommendations for the application of WSP sources. However, these common soil tests can underestimate (e.g. Bray I and Olsen) or overestimate (e.g. Bray II and Mehlich I) P availability in soils fertilized with water-insoluble PR. Separate calibration curves are needed for these two types of P fertilizer. Thus, the issue of developing suitable soil P testing methods for PR application brings a new dimension to phosphate research. There is need to develop appropriate soil tests that reflect P availability closely across a wide range of soil properties, PR sources and crop genotypes. Furthermore, soil tests should be suitable for both PRs and WSP fertilizers. Two recently developed soil tests show promise in soils fertilized with WSP and with PR sources. These are the iron-oxide-impregnated filter-paper strip test and the mixed cation-anion exchange resin membrane test. In both cases, the P extracted simulates P sorption by plant roots without the chemical reaction involved in the conventional tests. Available P measured in soils treated with both PR and WSP sources has shown: (i) good correlation with plant response; and (ii) both PR and WSP sources follow the same calibration curve. Further field trials are needed in order to test their suitability for developing recommendations for DAPR.

In order to provide sound guidelines for DAPR, it is essential to predict their agronomic effectiveness, crop yield increases and profitability. Several factors affect PR dissolution in soil under a specified set of conditions. DAPR as a P fertilizer is a more complex issue that involves consideration of a number of factors and their interactions. The development of a decision-support system (DSS) is the most effective approach for integrating all these factors and for providing an effective means of transferring research results to extension services. DSSs have been constructed to utilize available information to predict whether a given PR will be effective in a given crop environment. This publication discusses different types of DSSs, including the approaches adopted to develop a PR-DSS in New Zealand and Australia. It describes joint efforts currently underway by the International Centre for Soil Fertility and Agricultural Development (IFDC) and the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture (FAO/IAEA) to develop a more global DSS for use in tropical and subtropical countries for a range of food crops. Moreover, the PR-DSS could be linked to the phosphate model of the Decision Support System for Agrotechnology Transfer (DSSAT) family to predict crop yields, and GIS-based maps of crop response to PRs could also be compiled.

Phosphate-bearing minerals show a complex structure as a result of their geological origin and weathering processes. Their mineralogical and chemical composition is extremely variable. DAPR studies have focused mainly on the use of PR as a P source for crop production in acid soils, while limited research has been conducted on the effect of other beneficial and hazardous elements associated with PR use. Available information has suggested that PRs may also have potential agronomic value by provide some secondary nutrients, such as Ca and magnesium, and micronutrients, such as zinc and molybdenum, for plant growth depending on the type of PR sources. Reactive PRs containing free carbonates (calcite and dolomite) have been shown to reduce aluminium (Al) saturation of acid soils by raising soil pH and hence decreasing Al toxicity to plants. Limited studies also suggest that plant uptake of toxic heavy metals, notably cadmium, from PR is significantly lower than from WSP fertilizers produced from the same PR. More research is needed to investigate secondary nutrients, micronutrients, liming effect, and hazardous elements associated with PR use.

Not all PR sources are suitable for direct application. However, it is possible to utilize several means to improve their agronomic effectiveness under a particular set of condition. Selecting the appropriate process requires a good understanding of the factors hindering the agronomic effectiveness. The biological means (e.g. phospho-composting, inoculation with vesicular-arbuscular mycorrhizae, use of phosphate solubilizing micro-organisms, and use of P-efficient plant genotypes) are based on the production of organic acids to enhance PR dissolution and P availability to plants, and they hold good promise. The use of chemical means to produce partially acidulated PR (PAPR) is the most effective way of increasing the agronomic effectiveness of PRs and also saves energy. However, the production of PAPRs still requires fertilizer manufacturing plants. The physical means of dry mixing PR with a defined proportion of WSP fertilizer is promising and cost-effective. This simple approach should be promoted and evaluated under local soil and climate conditions.

Fertilizer legislation exists in many countries, especially developing ones. Its aim is to ensure that the fertilizer qualities meet the specifications set by the government in order to protect consumers' interests. As the bulk of PR production is utilized for WSP fertilizer manufacturing, only limited information on the legislation for DAPR is available. The agronomic effectiveness of PR for direct application depends on several factors and their specific interactions. Regulations for DAPR should consider three main factors: PR reactivity (solubility), soil properties (mainly soil pH) and crop species. Current legislation on PR for direct application considers only the quality of the PR, namely: total phosphorus pentoxide (P_2O_5) content, particle size distribution, and solubility. Based on recent research findings, this publication proposes several guidelines relating to issues on PR solubility and their interactions in a complex soil-plant system and concerning the establishment and revision of existing legislation.

In addition to technical considerations, a number of socio-economic factors and policy issues will determine PR production, distribution, adoption and use by the farmers. In principle, the use of PR sources should be promoted in countries where they are indigenously available. In countries with no PR deposits, it would be advisable to have a wide range of PRs available on the market in order to encourage price competition.

In conclusion, the appropriate and sound direct application of PR can contribute significantly towards sustainable agricultural intensification using natural plant nutrient resources. Although there has recently been substantial progress in scientific knowledge and technological developments on DAPR, further exploration of the specific issues is imperative.